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Text-Book of Petrology

VOLUME ONE

THE PETROLOGY OF THE IGNEOUS ROCKS

Text-Book of Petrology

VOLUME TWO

THE SEDIMENTARY ROCKS

*A Description of the Sediments and their
Metamorphic Derivatives*

Third Edition

Revised by Dr. Maurice Black

BY

A. K. WELLS

OUTLINE OF HISTORICAL GEOLOGY

Second Edition revised with the assistance
of J. F. KIRKALDY

227

THE PETROLOGY OF THE IGNEOUS ROCKS

THE LATE

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17660

REWRITTEN TENTH EDITION



THOMAS MURBY & CO

40 MUSEUM STREET LONDON W.C.1

proprietors: GEORGE ALLEN & UNWIN LTD

552.1
H.W.V.

First Edition, January 1891
Second Edition, October 1892
Third Edition, January 1903
Fourth Edition, September 1905
Fifth Edition, January 1909
Sixth Edition, June 1910
Seventh Edition, January 1914
Eighth Edition, February 1926
Ninth Edition, January 1937
Tenth Edition, entirely revised, 1949
Eleventh Impression, 1952
Twelfth Impression, 1956

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PREFACE

THE first edition of this book, a slender volume of 128 pages, appeared in 1891. In 1926, one of us (A.K.W.) joined Dr. Hatch in a complete revision. Ten years later, after the death of Dr. Hatch, rather more drastic alterations were made in the scheme of classification, mode of occurrence being dropped in favour of degree of crystallinity (grain size). As a consequence of discussion with successive generations of students and others interested in rock classification and nomenclature, it became obvious that another change was overdue. In the earlier editions, following an old-established practice, silica percentage was used arbitrarily as a main prop of the scheme of classification. For reasons that are discussed in the text this position can no longer be maintained, and instead of silica percentage we attempt to base the classification primarily on the mineral contents of the rocks.

Apart from this, the style of the book is not fundamentally altered, though the balance of its parts is changed. The fundamental principles underlying the petrological microscope—the principal instrument at the disposal of the working petrologist—are explained in, we hope, simple terms that will not shock the physicist. Rather more detail concerning the atomic structure of selected minerals has been introduced as a means to an end. A mental picture of the fundamental structure, from which a statement of the chemical composition can easily be inferred, is far more readily retained in the mind than a complicated formula. The latter takes on a new significance when it is related to a structural model or diagram. The diagrams of such structures are admittedly generalized and diagrammatic; but they serve a useful purpose. Much of the data concerning the physical properties of the minerals is omitted from this account, and this has allowed fuller discussion of the rôle of these minerals as rock-formers—the most important aspect for the petrologist.

In view of the modern tendency to explain many petrogenetic problems in terms of emanations, ionic migration and "granitization," a section of the book has been set aside for the consideration of these matters. The solution of the problems is very elusive and lies a long way ahead. In the meantime the authors' main purpose is to present the facts concerning the composition of the igneous, or eruptive, rocks as some prefer to call them, to direct attention to the interrelations between the component minerals, and between the various rock-types, regardless of their ultimate origins.

The great need among petrologists at the moment is a common

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system of nomenclature, and this must be based upon agreed definitions of the rock types under consideration. It is hoped that by discussion and comment in the following chapters a contribution will have been made towards achieving this end.

The senior author has enjoyed the privilege of working with his son on the tenth and eleventh editions. Large parts of the new additions, especially in Parts II and IV, are from the pen of the latter, as are all the new maps in Part V and a number of other illustrations in the text. The majority of the illustrations in the pre-1926 editions have now been replaced. A special feature has been made of large-sized drawings, which have been preferred to photomicrographs, and it is hoped that their study will help the student in the appreciation of the finer points of micro-petrology. From our experience in making these drawings we can say that there is no more effective way of seeing and comprehending these features than by making an accurate drawing of them. Many of the rocks illustrated are well-known examples of their kind, some few are rarities: there will be little difficulty in matching most of them in standard teaching collections.

A. KINGSLEY WELLS

August 1951

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INTRODUCTION

THE NATURE OF THE IGNEOUS ROCKS

PETROLOGY is that branch of geological science which has for its special field of study the rocks of the earth's crust. A **rock** is a mineral aggregate: it may consist of one mineral or many; it may be amorphous or crystalline. Its constituent mineral grains may be of such size that they are readily identified on inspection; or they may be so finely crystalline as to be resolvable only in thin section under the microscope. In studying rocks it is necessary to appreciate their field relations—their mode of occurrence and their associates; to determine the kinds of minerals present, and at least their relative abundance; and lastly to comprehend the mutual relationships between the individual components.

It is customary to recognize three main categories of rocks: the **sedimentary**, the **metamorphic**, and the **igneous or eruptive**. The first need no further comment in this volume. The second comprise all those rocks which have been changed in mineral content, in texture, or both, as a consequence of drastic change of environment. The chief agents active in metamorphism are high temperature and great pressure. If the rise of temperature and increase of pressure have been sufficiently drastic, a coarsely crystalline rock may result which will differ from an igneous rock in no obvious respect. The borderline between the metamorphic and the igneous is ill-defined and gradational. Nothing is easier than to select types from both categories which, on the most casual inspection, are seen to be completely distinctive; but the products of high grade metamorphism may simulate igneous rocks so closely that, divorced from their environment, they are virtually indistinguishable. The fact is that whether such a rock is classified as igneous or metamorphic is a matter of secondary importance: this depends less upon the individual characters of the rock than on its origin; that is, this ultimate classification into one or other category depends more upon what the rock was at some previous time, than upon what it is now. But a named rock-type consists of specified mineral grains with a definite mutual arrangement or **texture**. Apart from these observable facts, a rock has no individuality, and its pedigree is of no significance in choosing a name for it. A given rock-type may have originated in half a dozen different ways; but only one name is necessary—with qualifiers, if it is thought necessary to use them. Thus there may be metamorphic granites, metasomatic granites and magmatic granites. They all consist of the same minerals

arranged essentially in the same way; nothing would be gained by describing them under three categories when they are one and the same rock.

These problems of classification and nomenclature do not arise, of course, when dealing with average igneous and metamorphic rocks. A. Harker was in no more doubt concerning the subject-matter of his book on metamorphism and the metamorphic rocks than are the present authors in regard to what they propose to include in the present volume as igneous rocks. Much metamorphism is intimately connected with, and attributable to, igneous activity; on the other hand it appears probable that some phases of metamorphism are a prelude to igneous activity.

Formerly it was believed that all igneous rocks were magmatic. Today it is believed in many quarters that certain rocks "of igneous aspect" have not passed through the magmatic condition. It is difficult to give a comprehensive definition of **magma**, though there is no doubt as to its nature, for samples are made available at every outpouring of lava from a volcanic vent. The composition of magma may be inferred, in part, from the study of the igneous rocks formed from it; but in every such case the rock represents a part only of the magma from which it was formed; other rocks from the same source, said to be **comagmatic**, represent other magma fractions, while inevitably not all of the original components of the magma now occur in the rocks—the more volatile components are lost. This gap in our knowledge of the composition of magma is partly filled from information gained by studying the gases evolved from active volcanoes. Similarly magmatic temperatures can be gauged by measurements made at the top of the lava column in Hawaii, for example. From these considerations it appears that magma is material of the earth's crust that through a great increase in energy has become liquified. It consists essentially of the substance of the igneous rock minerals in a condition of mutual solution, together with certain volatile constituents which are not normally included in the rocks. Magmatic temperatures vary with composition. Granitic magma is relatively low in the scale, some fractions of it are believed to crystallize at temperatures well under 575°C ; but the commonest type of magma (basaltic), contains minerals whose melting points, determined under experimental conditions, are over $1,800^{\circ}\text{C}$.

Volcanic phenomena similar to those observable today are easily recognizable in past geological periods back to the earliest. Further, denudation has laid bare the roots of the ancient volcanoes in some instances, thus exposing rock-bodies formed from magma-fractions that failed to reach the surface, and consequently consolidated under

a "roof" of rock. As the latter is a poor conductor of heat, such magma would lose its heat slowly, and an igneous rock of coarse grain would result. In an area of the type we have in mind rock bodies of various shapes and sizes may occur (they are considered in due course), and the rocks of which they are composed may vary widely in degree of crystallinity. Those of coarsest grain, termed **plutonites**, grade through those of medium grain-size into the finest, which may be partly, or in extreme cases wholly, in the condition of natural glass. The field relations of such rock-masses demonstrate a common origin. By close comparison with active volcanoes, the lavas are *known* to be magmatic; by reason of their field relations, and of their chemical and mineralogical composition, some associated plutonites are *inferred* to be magmatic also.

On account of the extremely complex composition of the igneous rocks, and because it is virtually impossible to imitate natural conditions in a laboratory, the experimental study of the crystallization of even a simple magma is impossible at present. Nevertheless, particularly at the Geophysical Laboratory at Washington, invaluable work on simple silicate melts has been carried out. It is significant that the theory built up around the results of these investigations is consistent with the relationships between the rock-forming minerals observed in thin rock-sections. It would be premature at this stage to carry the discussion of magmas¹ further; but one point must be emphasized. The use of the term "magmatic," applied to a rock, implies that it originated by crystallization from a fluid of complex composition. The fluid may have originated *in situ*, or it may have migrated, possibly for a great distance, from its point of origin. In a multitude of instances some part of it has been erupted at the surface as lava. Such rocks differ fundamentally, as regards origin, from those believed to have been produced by the selective replacement of solid rock minerals *in situ*. Rocks of this latter type are essentially metasomatic, and the products of **granitization**. According to this view, the original elements in the rocks so affected are believed to be redistributed; they receive a direct contribution of materials, largely in the ionic condition, from some unspecified deep-seated (and therefore presumably magmatic) source. These are selectively assimilated and in the course of a general recrystallization the end-product is a crystalline silicate rock identical in composition and texture with a normal igneous rock, irrespective of the original composition of the material undergoing granitization. As might be expected, this is a hypothesis upon which expert opinion is sharply divided: it is as difficult to

¹ The student is recommended to study N. L. Bowen's address on "Magmas," in *Bull. Geol. Soc. America*, vol. 58 (1947), p. 263.

prove as to disprove. It is based primarily upon the interpretation of field evidence at the margins of granitic rock-bodies, and such evidence is, of course, subject to the human factor.

Now given that granitization does all that is claimed for it and that certain crystalline silicate rocks have been evolved by the process postulated, they are not only rocks "of igneous aspect," but also so closely resemble igneous rocks in composition and texture as to be inseparable from them. In other words, their affinities are with the igneous rocks, and they definitely fall within the present field of study. The specific qualities of these rocks are *facts* of composition and texture, and are completely independent of any theories which may be held regarding their pedigree.

That aspect of petrology which is concerned with the origins of rock-types is termed **petrogenesis**; while **petrography** is concerned with the facts of mineral and chemical composition and internal structure or texture. The study of mineralogical and textural similarities and dissimilarities leads to the definition and classification of rock-types. In this volume we are concerned chiefly with petrography, though petrogenetic considerations are by no means excluded, especially when evidence of origin seems to be afforded by the rocks themselves.

PART I

*THE ROCK-FORMING MINERALS
OF THE
IGNEOUS ROCKS*



OPTICAL PROPERTIES

WHEN studying minerals in thin section with a view to identifying them, we take into consideration firstly their shapes, secondly their internal structures such as cleavage traces, evidence of twinning, occurrence of inclusions, and thirdly their optical characters.

(1) Shape or Form.

If the conditions that prevailed during crystallization of a mineral were such as to allow free growth, the crystal-form typical of the particular mineral species will be developed, and the shapes seen in thin sections will be bounded by natural crystal faces. Such minerals are said to be **euhedral** or **idiomorphic**. If, on the other hand, growth was impeded by the presence of crystals of other minerals of earlier formation, the development of the natural crystal-form is impossible and shapeless grains result. These are said to be **anhedral** (literally "without angles") or **xenomorphic** (with "stranger" shapes). If desired, an intermediate category may be distinguished as **subhedral**, or **subidiomorphic**.

Now obviously a mineral seen in thin section is far less distinctive, from the point of view of shape or form, than a complete crystal, seen in three dimensions: there can be no simple relationship between the solid form and a thin section of chance orientation, as may be readily appreciated by cutting sections in different directions through a cube—of potato for example.

Nevertheless, with practice, and with a well-developed three-dimensional sense, much may be inferred from the study of chance sections in a rock-slice; and there is always a possibility that a recognizable orientated section will be discovered, that goes far towards establishing the identity of the mineral under observation.

(2) Cleavage and Fracture.

Mineral cleavage takes place in directions determined by the presence of planes of weakness, due to the fact that in these planes, the atoms are fewest and the electrical bonds are weakest. In using cleavage two factors are involved: first, the direction of the cleavage, and secondly its degree of perfection. The former is defined by reference to its parallelism to crystal faces: thus one speaks of a basal cleavage, or cleavage parallel to (001). One practical point

arises here. Cleavage traces appear most perfect and most clearly defined when they are perpendicular to the plane of the slide, and other things being equal are better developed in crystals round the edge of the slide than in grains of the same mineral embedded in the middle of the section. Not infrequently, cleavage is accentuated by incipient alteration along these planes of weakness.

(3) *Refractive Index and Surface Relief.*

It is a matter of common knowledge that the velocity of light changes on passing from one medium to another and this causes a change in the direction of the ray of light at the surface of separation between the two. This phenomenon is refraction, and the degree of refraction is the ratio between the two velocities, *i.e.*, the refractive index. Differences in refractive index of minerals form the basis of practically all the methods of determining minerals in thin sections with the aid of the petrological microscope.

Among common rock-forming minerals refractive indices range from 1.43, for fluorite, to 2.76 for rutile. At first sight this does not appear to be a wide range; but a very small difference, say in the third place of decimals, may produce striking effects.

Surface relief involves the distinctness of the outline of a mineral grain, and the appearance of its surface. Both these features are dependent upon the difference in refractive index between the grain and the medium, generally Canada balsam, in which it is embedded. Theoretically, if grain and medium have the same refractive indices, the former should be invisible. If there is a slight difference, the grain will be faintly outlined, and its surface will be smooth. If there is a large difference, the grain will be heavily outlined and the surface will appear rough as if minutely pitted. These observations should be carried out with the iris diaphragm carefully manipulated: there is an optimum "stop" which will ensure maximum surface relief, but adequate illumination. Further, care must be taken to ensure that there is not too much "top light," which may give a completely wrong impression through surface reflections. Momentarily shading the stage with the hand will immediately show whether some more permanent form of screening is required or not.

The virtual disappearance of a grain on immersion in a medium with the same refractive index is the basis of one of the most important operations in determinative micro-petrology—the measurement of refractive indices by the **immersion method**. In briefest outline this involves examining the mineral under test—only a small fragment is required—when immersed in different liquids until one is found which exactly matches the grain in refractive index. Then the index of the liquid is measured on a refractometer. With a first-

class instrument it is possible to measure the refractive index correctly to four or even five places of decimals. The full details of the method will be found in a text-book of petrographic methods. This is research technique however; but the same principle is involved in the standard method of comparison between the indices of two grains in juxtaposition. The diaphragm is closed until the field begins to darken. On slightly raising or lowering the tube of the microscope, using the fine adjustment, a bright line will be seen near the boundary. As the focus is changed the bright line crosses the boundary in accordance with the following rule: on focusing down, the bright line moves from the substance of high to that of low refractive index, and, of course, conversely. This is a very delicate test if carried out with reasonable care. It may be used to compare a grain on the edge of a slide with the balsam in which the latter is embedded. The result of the test may well establish the identification of the mineral under examination. This is called the **Becke Test** after its discoverer.

(4) *Double Refraction.*

With few exceptions minerals cause a ray of light passing through them to be resolved into two components, vibrating in two different directions at right angles to one another, and refracted to different extents. This is the phenomenon of double refraction. One of the component vibrations behaves as it would in an isotropic, non-directional medium such as glass, and is called the *ordinary ray*; but the other, appearing to disobey the ordinary laws of refraction, is referred to as the *extraordinary ray*. The fact of double refraction, as produced by calcite, and the difference between the ordinary and extraordinary components, may be readily observed if a cleavage rhomb of clear calcite is placed over an ink spot on a white sheet of paper. Two images are seen, at slightly different levels in the calcite, and on rotation of the latter, one image remains stationary, while the other rotates with the calcite. The latter is the image due to the extraordinary rays.

(5) *Optical Orientation.*

Cubic minerals such as fluorite possess only one refractive index, for light passes with equal ease, and therefore with the same velocity, in all directions in the mineral. All other minerals fall into two categories: the one includes those which crystallize in the systems characterized by one principal, and either two or three equal lateral axes—that is, in the Tetragonal, Hexagonal and Trigonal systems. In these minerals there is one, but only one, direction of single

refraction. Light which is transmitted along this direction is not doubly refracted. This unique direction within the crystal is its optic axis, which is, in all cases, parallel to the principal crystallographic axis. The minerals in this class are said to be **uniaxial**. Minerals which crystallize in the remaining systems, *i.e.* the Orthorhombic, Monoclinic and Triclinic, are **biaxial**, as they contain two directions of single refraction—two optic axes. The acute angle between the optic axes is denoted by $2V$ if measured in the mineral, or $2E$ if measured in air.

If the smallest refractive index in a mineral is represented by N_a , or more simply by α , and the greatest by N_γ or γ , the former is the index of the fastest ray, which is denoted by X; while the index γ is that of the slowest vibration, Z. In uniaxial crystals the light vibrating parallel to the optic axis is the fast vibration (X) in some cases, but the slow vibration (Z) in others. These two categories are distinguished as "negative" and "positive" respectively. In practice, it is preferable to think in terms of fast or slow vibrations rather than of large or small refractive indices, because the relative velocities are quickly and easily compared by means of the accessory plates, the gypsum and mica plates and the quartz wedge, which form part of the normal equipment of the petrological microscope.

With biaxial minerals the optical orientation is more involved, as now it is necessary to recognize three vibration directions, X, Y and Z, corresponding with three refractive indices, α , β and γ .

In an **Orthorhombic crystal** symmetry demands that X, Y and Z should correspond with the crystal axes, a , b and c ; but as each of the latter may be any one of the former, there are six possible settings:—

a	—	X	X	Y	Y	Z	Z
b	—	Y	Z	X	Z	Y	X
c	—	Z	Y	Z	X	X	Y

The X and Z directions invariably lie in the plane which contains the optic axes, and bisect the angles between them. They are therefore known as the bisectrices: Bx_a , the **acute bisectrix**, in the acute angle between the optic axes, and Bx_o , the **obtuse bisectrix**, at right angles to it. The plane containing the bisectrices, acute and obtuse, and the optic axes is the **optic axial plane**, which must, of necessity, lie parallel to one of the planes of crystallographic symmetry. Which of the three actually corresponds to the optic axial plane is best stated by giving the indices of the corresponding pinacoid. In the case illustrated in Fig. 1 the optic axial plane is parallel to (010). The third vibration direction (Y) corresponds to a velocity between X and Z, with index β of value intermediate

between α and γ . From its relationship to the optic axial plane, it is called the **optic normal**, Y.

Having thus fixed the position of the optic axial plane, from what has already been said, it will be realized that within this plane, each of the crystal axes can be, in different cases, either Bx_a or Bx_o . Which of the two possibilities is appropriate in a given instance is stated by specifying to which pinacoid the Bx_a is perpendicular. In Fig. 1 Bx_a is perpendicular to (100).

Finally, with this setting of the optic axial plane and the bisec-

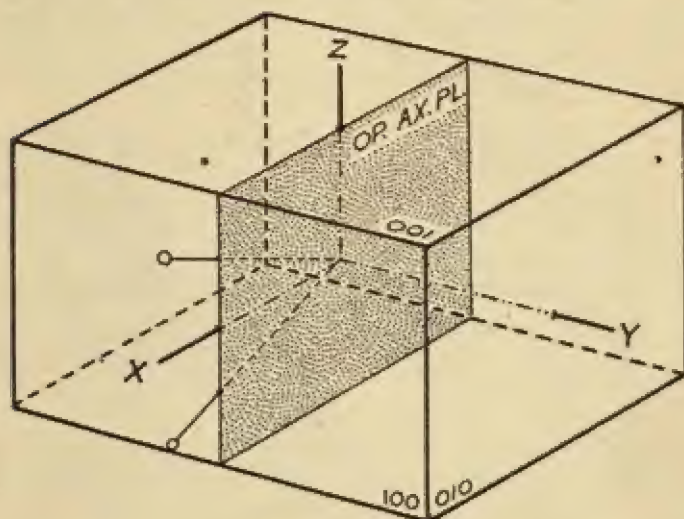


FIG. 1

Diagram illustrating one optical orientation of an Orthorhombic mineral.

OP. AX. PL. = optic axial plane.

The optic axes are symmetrically disposed about X and are marked by small rings.

trices, Bx_a may correspond with Z, in which case the mineral is optically positive; or it may be X, when it is optically negative.

In **Monoclinic minerals** the nomenclature is the same, but the orientation is consistent with the lower symmetry. The single diad axis, b , must correspond with one of the vibration directions, X, Y or Z, while the other two must obviously lie in the single plane of crystallographic symmetry. In general terms two cases are possible: in the one, the diad axis is the optic normal, Y, and therefore the plane of crystallographic symmetry coincides with the optic axial plane (Fig. 2). On the other hand, if the diad axis is either the acute or the obtuse bisectrix, the optic axial plane must be at right angles

to the plane of symmetry as illustrated in Fig. 3. In this case the exact position of the optic axial plane is best fixed by stating the angle between it and basal pinacoid, or the basal cleavage when the latter is developed. Now, as the angle between the vertical and clino-axes cannot be 90° in a Monoclinic crystal, and as the vibrations X and Z must be perpendicular to one another, it follows that the latter cannot both coincide with the former; indeed the bisectrices may take up *any position* in the optic axial plane. It is usual to fix their position by stating the angle between the slow vibration, Z,

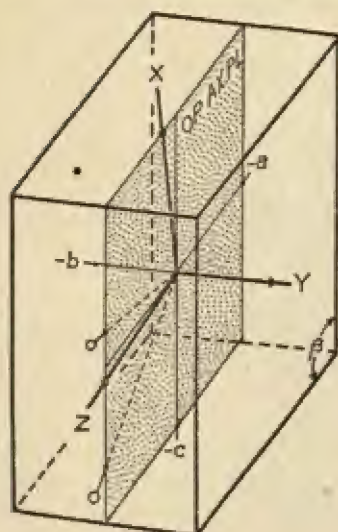


FIG. 2.

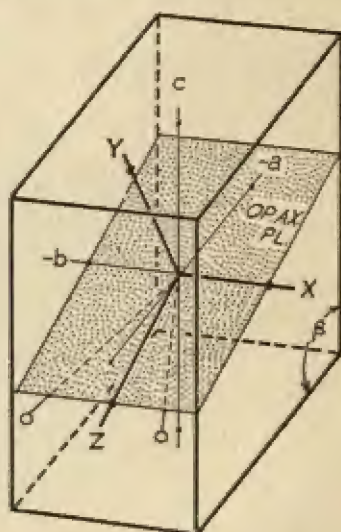


FIG. 3

Diagrams showing the optical orientation of Monoclinic minerals. Optic axial plane stippled; optic axes marked by small rings; crystal axes, a , b and c , thin lines.

and the vertical axis, c , often indicated in appropriate thin sections by prismatic cleavage traces.

It would be unprofitable at this stage to discuss the optical orientation of Triclinic minerals. We need only note that X, Y and Z need not coincide with any of the crystal axes.

So far we have dealt merely with the fact of double refraction. It remains to study some of its consequences.

(6) *Pleochroism.*

The directional properties of minerals are strikingly demonstrated by the fact that equal thicknesses viewed in different directions may

be differently coloured. This property of differential absorption or pleochroism is of great value in determinative mineralogy. Pleochroism may be strikingly demonstrated by a prism of tourmaline held with its axis parallel to a plate of polaroid with a strong light behind it. On turning the tourmaline from the vertical to the horizontal position, the change of colour, in some specimens, is almost dramatic.

One of the chief purposes of fitting the petrological microscope with a rotatable stage is to make it easy to observe and record these colour changes. The polarizer in the microscope causes plane polarization of the light which passes through it. Suppose the direction of

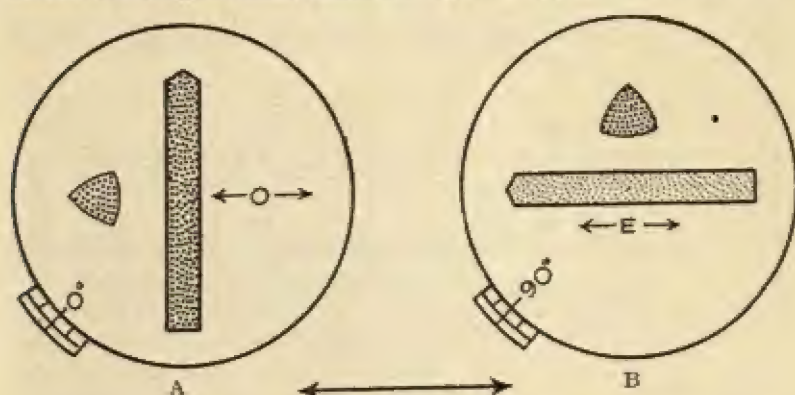


FIG. 4

Diagrams illustrating the Pleochroism of Tourmaline, with absorption formula $O > E$.

Vibration direction of polarizer indicated by the arrow below the circles, and of the ordinary and extraordinary rays in the tourmaline by arrows with the letters O and E respectively. The basal sections show no change on rotation over the polarizer.

vibration to be left to right. If now a prism of tourmaline in a section on the stage is rotated until its axis is vertical, it must be illuminated by polarized light vibrating left to right, i.e. at right angles to its optic axis (Fig. 4A). Now this is the vibration direction of the ordinary component in the crystal, and the colour seen is that due to the ordinary ray. When the crystal is rotated until its principal axis lies left-and-right, it is illuminated by the extraordinary component, and the colour seen is that due to the extraordinary ray (Fig. 4B). It will be noted that the absorption of the ordinary is much greater than that of the extraordinary ray for tourmaline; but the opposite is sometimes true of other minerals, so that a statement of the "absorption formula" is necessary. Thus for tourmaline, absorption is "O" > "E."

With biaxial minerals, all three vibration directions, X, Y and Z, may display differences of absorption. The complete **pleochroism formula** is derived by bringing the vibration directions successively into parallelism with the vibration direction of the polarizer, and noting down the colours, and for the purposes of recording the **absorption formula**, the relative strengths of the colours must be noted at the same time. Reference to Fig. 1 will make it clear that for each of the pinacoidal sections, the light will be transmitted along one axis, but will vibrate parallel to the other two. With a Monoclinic mineral having the optical orientation illustrated in Fig. 2, the (010) section will show successively the colours due to X and Z on rotating the stage; but the colour due to Y will be seen in a basal section when the *b*-axis is lying parallel to the vibration direction of the polarizer.

(7) *Extinction.*

When a mineral of doubly refracting type is observed between crossed nicols (or crossed polaroids) while the stage is rotated, it is perhaps brilliantly illuminated in certain positions, but is completely dark in others. When it has been turned into the dark position, the light from the polarizer is passing straight through the section, but none of it is allowed to reach the eye, as all of it is deflected by the analyser. Therefore the vibration directions in the mineral slice now lie parallel to those of the polarizer and analyser, that is, parallel to the "cross-wires" in the eyepiece. Only by turning the section into the extinction position can the vibration directions be ascertained. As the latter are mutually at right angles to one another, it follows that a section must extinguish four times in a complete rotation of the stage.

Certain sections, when lying in the extinction position, may exhibit internal structural features, notably cleavage traces, also aligned parallel to one of the cross-wires. Such a section has *straight or parallel extinction*. Alternatively the cleavage traces and the cross-wires are not parallel in sections showing *oblique extinction*. It should be carefully noted that one speaks of the extinction of the section—not of the mineral, for it is impossible to state a general rule that will cover the extinction of all sections of a particular mineral. Far too often it is assumed that all sections of the same mineral must exhibit the same kind of extinction. This is not the case. The Monoclinic silicate minerals such as augite and hornblende exhibit straight, oblique (very widely oblique in the case of augite), or symmetrical extinction, in differently orientated sections. The details are discussed under the descriptions of the minerals named. Even in Orthorhombic minerals, sections extinguish straight only in

the "principal sections," that is, those which lie in zones parallel to one or other of the crystal axes. A section parallel to a bipyramid face, on the other hand, may extinguish at a wide angle.

(8) *Birefringence and Interference Phenomena.*

Literally, a mineral is birefringent if it causes double refraction. The most spectacular result of double refraction is the production of interference colours when a mineral section is viewed between "crossed polarizers." This property is of the greatest value in the identification of minerals through their optical reactions under the microscope. Even superficial examination of the interference colour will show immediately whether the refractive indices of the two sets of vibrations involved are closely similar, or widely separated. More specifically, the birefringence of a mineral is *judged* by the nature of the interference colours it produces; it is *measured* by the difference between the refractive indices of the rays of maximum and minimum velocity passing through it. In theory the measurement of the birefringence would involve the determination of the refractive indices of the fast and slow rays in the mineral; but in practice good results may be achieved by studying the interference colours. The measure of the birefringence is $(\gamma - \alpha)$; but these values apply to certain sections only: to vertical sections, parallel to the optic axis, in uniaxial minerals, and to sections parallel to the optic axial plane in biaxial minerals. These sections will produce the brightest interference colours; but in a rock-slice there will be other sections, of different orientation, which will yield duller colours; while those cut perpendicular to an optic axis will produce no double refraction and therefore show no interference colour whatever.¹

As specific illustrations we may quote quartz and olivine.

For quartz $\gamma = 1.553$	For olivine $\gamma = 1.670$
$\alpha = 1.544$	$\alpha = 1.635$
$\gamma - \alpha = 0.009$	$\gamma - \alpha = 0.035$

Thus the specific (or maximum) birefringence of quartz is 0.009. This value is appropriate to a vertical section only, and in a slice of normal thickness the interference colour is yellowish white. In a thin section of quartzite consisting of grains of quartz lying in all possible azimuths, every gradation will be seen between this yellowish white through shades of grey to the completely black basal section.

In the study of birefringence a **birefringence table** is essential.

¹ This is true for uniaxial minerals, and approximately true for biaxial minerals. Actually in the latter case the section is not quite black, but a dull grey.

This is a coloured chart, showing several orders of "Newton's scale," *i.e.* the colours of the spectrum, arranged in the order in which they are displayed by a quartz wedge. The first order ranges from dark grey, through greyish white, yellowish white, into yellow, orange and red to purple. The second and subsequent orders pass from blue into green, then yellow, orange, red and purple again. The scale of colours is graduated in order that one may refer specifically to a certain shade of colour, which is much more satisfactory than attempting to state what it is in words. The *scale-value of an interference colour* is the product of three quantities; the difference in refractive index of the two rays, and the thickness of the slide, multiplied by 1000 to give the value as a whole number. An average thickness for a section of modern make is 30 microns (0.030 mm.). Therefore it follows that the scale-value of the interference colour of the section of quartz referred to above is:— $0.009 \times 30 \times 1000 = 270$. By comparison, a section of olivine cut parallel to its optic axial plane would show a colour with scale-value of $0.035 \times 30 \times 1000 = 1050$, corresponding to a light orange-red in the 2nd order. Apart from the actual values of the colours, the birefringence of quartz is said to be *weak*, that of olivine, *strong*.

(9) Dispersion.

In studying the interference colours of some minerals, it may be observed that certain sections fail to extinguish completely: they pass in a matter of a few degrees rotation of the stage from one deep tone to another, but never go completely dark. This is a consequence of dispersion—the separation of white light into its components to such a degree that the plane of vibration for red light may be appreciably different from that for blue. There are several different kinds of dispersion, but the phenomena are best left to the advanced petrologist who has at his disposal the necessary apparatus for studying sections illuminated with monochromatic light of varied wavelength.

(10) Interference Figures.

Valuable information concerning the optical orientation of a mineral section may be gained by examining it with a high-power objective, using powerful, *convergent* light. Under these conditions an interference figure should be obtained; and although these are often difficult to interpret, they do provide a means of distinguishing uniaxial from biaxial minerals, of finding the optical sign and the positions of the optic axial plane and bisectrices. The most informative sections are those cut perpendicular to the optic axis of a uniaxial mineral, and at right angles to the acute bisectrix in a biaxial

one. In an average section the chances are heavily against finding one of these ideally cut sections, so the figure displayed seldom shows its full symmetry, and its interpretation calls for a good three-dimensional sense on the part of the examiner.



FIG. 5

Diagrammatic representation of Interference Figures

The stippling represents bands of interference colours, and the black areas the positions of isogyres. (A) uniaxial figure: the optic axis emerges at the centre of the cross; (B) biaxial figure of acute bisectrix: $2V$ is small and the isogyres approach each other, simulating a uniaxial figure; (C) biaxial figure of a mineral with moderately large $2V$.

In Fig. 5 three ideal cases are illustrated: a uniaxial (left), a biaxial (right) and a pseudo-uniaxial (middle) interference figure respectively. The biaxial figures are drawn with the optic axial plane in the 45° position, and the degree of separation of the two black hyperbolae suggests the size of $2V$. These three cases represent a continuous series in which the optic axial angle progressively decreases until it becomes zero. Thus the uniaxial mineral is the limiting case of the biaxial.

The *optical sign*, whether positive or negative, may be readily deduced from the changes in the interference figure seen on introducing the accessory plates. In brief, if the vibration parallel to the unique optic axis in a uniaxial mineral, or to the acute bisectrix in a biaxial one is slow, the mineral is positive, and conversely.

DESCRIPTION OF THE CHIEF MINERAL GROUPS

(1) Introduction: Classification.

THE rock-forming minerals may be variously classified, according to the part played by them in the structure and composition of rocks. A useful division is into **primary** and **secondary**, the former being further divisible into essential and accessory. An **essential** mineral is one whose presence is implied in the definition of the rock. An **accessory** mineral is one whose presence or absence does not sensibly affect the character of the rock. Thus, quartz, feldspar and mica are essential constituents of granite; while zircon, sphene and apatite are accessory. It should be realized that an occasional accessory mineral in one rock may become an important essential in another. For example, although quartz is an accessory in some gabbros, it is the characteristic mineral of granites, and no rock free from quartz can be termed granite. The accessory minerals are sparsely distributed; but although only one or two may be seen in a hand specimen, others come to light when thin sections are examined. To make a complete list, samples of the rock must be crushed and the heavier minerals separated by liquids of high specific gravity. This method has been successfully applied in the study of a number of igneous rocks, and has resulted in a considerable advance in our knowledge of the distribution of the more uncommon constituents.¹ Many of these accessory minerals are among the most stable and most durable components of igneous rocks. They thus persist after the essential minerals have been destroyed by weathering, and by their presence add distinctiveness to the sands and other sediments formed by the degradation of igneous rocks. Their detailed study is now an important branch of petrology (see Vol. II of this work).

Minerals are **secondary** when they have resulted from the alteration or reconstruction of the original minerals (by weathering, or as a result of metamorphism). In altered rocks both essential and accessory minerals may be replaced by secondary ones.

It should be noted that a mineral may be primary in one rock, but secondary in another; thus primary quartz occurs in granite while secondary quartz is liberated as a result of weathering of several species of rock-forming minerals.

¹ See, for example, Rastall and Wilcockson, *Quart. Journ. Geol. Soc.*, lxxi (1915), p. 592.

In the following account, as far as practicable the primary essential minerals of igneous rocks are described first, followed by the characteristic secondary minerals formed from them by weathering or otherwise. Then the accessory minerals are described, roughly grouped according to mode of origin. There is some inevitable overlap between these different categories.

As it is not our intention to attempt to compete with standard text-books on mineralogy, much detail concerning the physical properties of the minerals has been omitted: such detail, if required, can be readily obtained from one of the standard works of reference.

(2) *Considerations concerning Atomic Structure.*

In these chapters the description of most groups of the rock-forming minerals is based on their atomic structure, as revealed by X-ray analysis. The actual technique involved in the latter, and the interpretation of the experimental data are matters for specialists; but the results of their researches are most illuminating to the student of mineralogy, particularly as regards the chemical relationships between allied mineral species, and the interdependence between physical characters and the intimate internal atomic structure. We have of necessity drawn largely upon W. L. Bragg's invaluable account of the atomic structure of minerals. One great difficulty arises in connection with using the results of X-ray analysis: it is far from easy to make a useful illustration representing an intricate atomic design in three dimensions. Those which we have introduced must be regarded only as diagrams—they are only first approximations to the truth; but as a teaching device they have their place, if for no other reason than that they help to make sense out of the otherwise meaningless string of symbols which represents the composition of any one of these minerals.

The component atoms or groups of atoms are held together by electrical forces of attraction between oppositely charged bodies of minute size. Those carrying a positive charge are termed **cations**; those with a negative charge are **anions**. For the sake of simplicity we may speak of the size of an atom, meaning the atomic radius, which is the distance, measured in Ångström units, at which mutual repulsion sets in when two atoms of the same kind approach one another.

In the essential minerals of igneous rocks we are dealing largely with silicates, *i.e.* combinations of silicon (Si) with oxygen (O), these being associated with cations in variety. Those commonly occurring include the following, in order of increasing size, the atomic radius being stated in brackets in each case:—

Si (0.39)	Na (0.98)
Al (0.57)	Ca (1.06)
Mg (0.78)	K (1.33)
Fe (0.83)	

The anions are much less varied. Among them oxygen (O, 1.32) plays the dominant rôle, but in certain minerals hydroxyl (OH, 1.32) or fluorine (F, 1.33) may replace it to a limited extent. Now all these anions are large compared with the cations; and we may regard the mineral structures as consisting of closely packed anions (chiefly oxygen), with the small cations tucked into the interstices between them. With some of the more complex minerals the number of kinds of atoms may be large, and the atomic design may be



FIG. 6

Tetrahedron and SiO_4 -group.

The small silicon atom is hidden between the four large oxygen atoms, each of which has its centre at a corner of the tetrahedron. The black spot shows a Si-atom to same scale as O-atoms.

exceedingly intricate; but just as an imposing modern skyscraper is built up of relatively insignificant blocks of building material, so these involved atomic structures may be resolved into simple units of structure. For our purposes only two such units need be recognized. In the first, four oxygen atoms are closely packed round a silicon atom, giving an SiO_4 -group. The oxygens lie at the corners of a tetrahedron, and the silicon is of such a size that it fits snugly into the interspace between them, as shown in Fig. 6. The second fundamental unit of structure comprises six oxygens in close contact, lying, as it were, at the corners of an octahedron. There is space between them for a larger cation than a silicon, and atoms of magnesium, aluminium or iron commonly occur in such "six-fold co-ordination" with the anions surrounding them. Each and every cation shares its charge, whether of one, two, three or four units, with all the anions by which it is immediately surrounded. Thus an Al^{+++} in the centre of an octahedral group of O's, has a positive charge of three units to share among the surrounding six O's, and therefore

contributes a charge of $+\frac{1}{2}$ to each. On the other hand, a silicon (tetravalent with a total charge of $+4$), in an SiO_4 tetrahedron, contributes $+1$ to each of the surrounding oxygens. This is "**Pauling's principle.**" In both cases cited, as oxygen is divalent, that is has a charge of 2 units, it follows that there must be a residual electrical charge on these units of structure. But the whole edifice is compounded of such units, packed together, with interspaces available for the introduction of as many cations as are necessary to balance out this residual negative charge. There must be no residual charge of the kind we have visualized, in a stable mineral. This necessity of balancing the total positive against the total negative

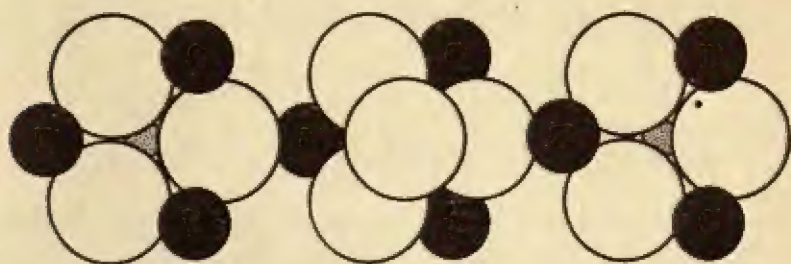


FIG. 7

The atomic structure of Olivine

A small portion of a single row of SiO_4 -tetrahedra with the associated cations, Mg and Fe, shown in black. This row is parallel to the b-axis.

charge provides a check on the accuracy of a formula representing the composition of a mineral.

In the following account we describe the essential rock-forming minerals in the order of increasing atomic complexity.

THE OLIVINE GROUP

This group comprises a number of important rock-forming silicates. In all members of the group the essential plan of the atomic structure is the same: isolated SiO_4 -tetrahedra are packed together in lines parallel to the crystal axes. In any such line parallel to the axis, they all point in the same direction (Fig. 7); but in alternate lines the tetrahedra point to the left and right, as shown in the spaced diagram of Fig. 8. The individual tetrahedra are joined one to another by the cations, which are arranged in six-fold co-ordination with the oxygen atoms, which, as the diagram shows, belong to different adjacent tetrahedra.

Thus the unit of structure is the single SiO_4 -tetrahedron. Against the negative charge of 8 units supplied by the oxygens, the Si^{++++}

offers a positive charge of 4 units; therefore on each tetrahedron a negative residual charge of 4 units remains to be balanced out by the addition of the requisite cations. In the several members of the olivine group the latter include Mg^{++} , Fe^{++} , and much less commonly Mn^{++} and Ca^{++} . If all the necessary cations are Mg^{++} , the formula becomes Mg_2SiO_4 , which corresponds to the natural mineral **forsterite**. If iron is used exclusively, the corresponding mineral is **fayalite**, represented by Fe_2SiO_4 . These two orthosilicates, as they are called, are the end-members of a continuously variable series, in

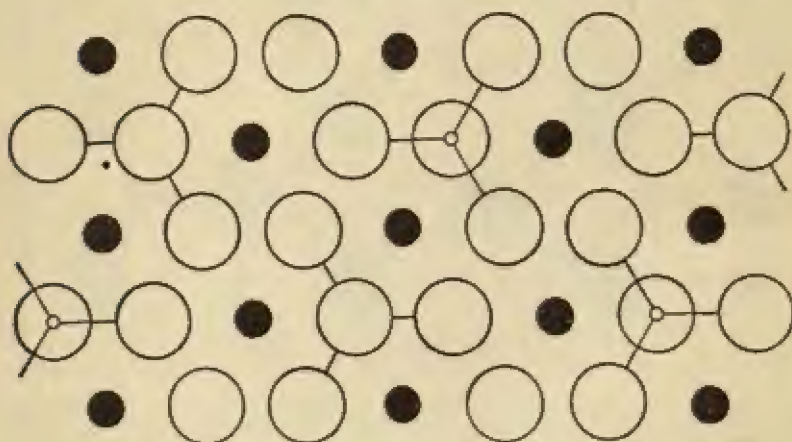


FIG. 8

The atomic structure of Olivine represented formally.

Large circles—oxygen; small circles—silicons; black—magnesiums and/or iron. Two rows of SiO_4 -tetrahedra are shown with their oxygens in planes parallel to (100). Each tetrahedron is associated with three metallic cations (Mg^{++} , Fe^{++}); these three are alternately behind (top row, left), and in front of, the tetrahedrons as shown in Fig. 7.

which the ratio of Mg to Fe varies from 100 : 0 to 0 : 100. Such a series may be subdivided arbitrarily into a number of mineral species, with agreed ranges of composition. Unfortunately, in this case, agreement has not yet been reached as to how many divisions should be erected, but we show two recent suggestions in Fig. 9. To avoid misconception it is necessary to use a symbol, in addition to, or instead of, the mineral name. The symbol indicates accurately the molecular percentage composition: thus if pure forsterite is represented by Fo and pure fayalite by Fa, the symbol $Fo_{33}Fa_{67}$ gives full information as to the composition of this particular specimen. As a matter of interest it may be noted that if names were used, this would be *hyalosiderite* (Wager and Deer), *chrysolite*

(Tomkeieff), but in the original description of the mineral it was called hortonolite.¹

The stability conditions controlling the crystallization of the members of this series have been studied experimentally.² Under laboratory conditions the temperatures of crystallization (melting

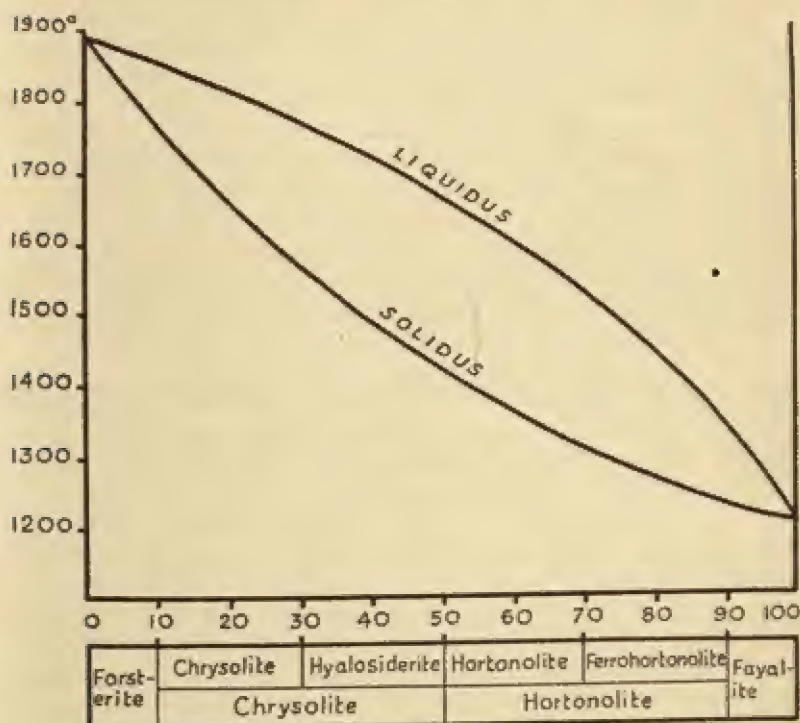


FIG. 9

Diagram showing the cooling curve for the Forsterite-Fayalite Series.

After Bowen, N. L. and Schairer, J. F.

The subdivisions of the olivine group as suggested by Wager, L. R. and Deer, W. A. (*Amer. Min.*, xxiv (1939), p. 25), and Tomkeieff, S. I. (*Min. Mag.*, xxv (1939), p. 229), are shown above and below respectively.

points) range from approximately 1,890° C. for pure forsterite to 1,205° for pure fayalite (Fig. 9). The diagram shows that for an olivine of composition Fo_{30} , crystallization commences at about 1,650° C., and that the first-formed crystals are considerably richer

¹ Wagner, P. A., *Platinum Deposits and Mines of S. Africa*, London, 1929, p. 55.

² Bowen, N. L. and Schairer, J. F., "The System MgO-FeO-SiO_2 ," *Amer. Journ. Sci.*, xxix (1935), p. 151.

in Mg than the original melt.¹ As the temperature falls, the composition of the growing crystals changes, becoming progressively richer in Fe. With relatively rapid cooling the successive layers of crystalline material may survive as distinct zones of different composition; the core in such a zoned crystal must be relatively rich in Fo, while the outermost zones must be correspondingly rich in Fa, the lower melting point component.²

Reasoning on similar lines, early-formed phenocrysts in a lava should be (and are) richer in Fo than the smaller crystals in the groundmass of the lava. Further, among the latter those of largest size, which presumably started growth early and at a relatively high temperature, are more richly magnesian than smaller ones, of later, lower-temperature formation.

The discovery of these facts concerning the variation of composition in successive crops of olivine crystals, and even within large single olivine crystals, is only possible if means exist for accurately determining the compositions of the specimens under consideration. Obviously careful chemical analysis will give the desired information; but there are certain less costly ways available to the petrologist. In any continuously variable series like the olivines, the physical, including the optical, properties vary systematically with the composition. Much useful data has accumulated from the study of isolated olivines, and has been used to construct curves showing these variations (Fig. 10). Two sets of measurements have proved valuable in this connection: (1) the size of the optic axial angle, $2V$ (measured in the mineral), or $2H$ (measured with the Universal stage); and (2) the refractive indices, more especially the mean index β measured with a refractometer. Unfortunately the actual measurement of these properties is a matter for the specialist: they involve methods and apparatus not normally available to students. It is not practicable to determine the composition of an olivine by any of the simple methods, such as extinction angle, used in other groups of minerals. While therefore one must be satisfied merely to identify the mineral generically, as it were, it is possible to go a long way towards specific identification in the light of the following facts concerning the distribution of the different members of the group.

Bowen and Schairer have shown experimentally that Mg-rich olivines—*forsterite*, *chrysolite* and *hortonolite* are unstable in the presence of free silica. Therefore under normal conditions, these

¹ Draw a vertical line from 50 to cut the *liquidus* curve, then a horizontal line through this point shows the temperature at which crystallization commences; while the point where the horizontal line cuts the *solidus* curve indicates the composition of the first-formed crystals.

² Tomkeieff, S. I., "Zoned Olivines and their Petrogenetic Significance," *Min. Mag.*, xxv (1939), p. 229.

members of the group are not found in association with quartz: no granitic rock can contain these members of the group. But olivine rich in Fe can exist in the presence of free silica, though even here there is a limitation: the temperature must be relatively low to bring it within the temperature-range of granitic magma. This is merely another way of stating that the only kind of olivine which can occur in a granitic association of minerals is nearly pure fayalite. The latter has now been recorded in a number of quartz-bearing

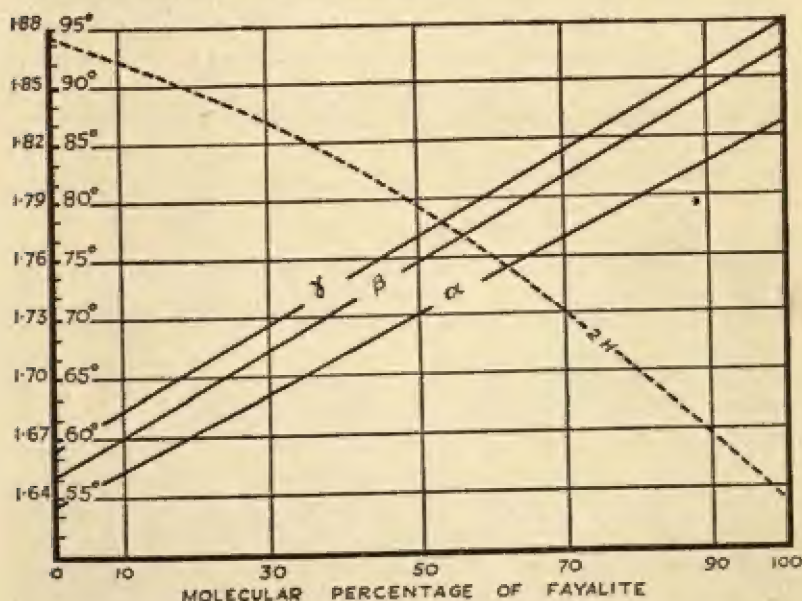


FIG. 10

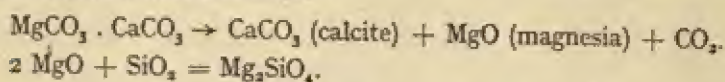
Diagram showing variation in the size of the optic axial angle $2H$, and refractive indices, in the olivine group. Data from Bowen and Schairer, Wager and Deer, and Tomkieteff.¹

rock-types including pitchstones from Arran, Scotland, obsidian from the Yellowstone Park, quartz-porphyrines and rhyolites from Nigeria, etc., but it still remains a relative rarity. The olivines, excluding forsterite and fayalite, are typically components of the silica-poor (basic and ultrabasic) igneous rocks. The amount is greatest in certain ultrabasic rocks, significantly termed olivinites and peridotites, and is only little less important in certain basic igneous rocks such as olivine-gabbros, troctolites, and olivine-basalts. Some of the last-named contain so-called "olivine-nodes," but these are really small pieces of peridotites that were picked up

¹ In Fig. 10, " $2H$ " is the optic axial angle measured on the universal stage.

by, and incorporated in, the magma during its uprise towards the surface. Well-known examples occur in the Carboniferous basalts in Derbyshire. Now in all these rocks there is a preponderance of the Fo-component over the Fa-component, and with few exceptions the general rule may be enunciated that the more basic the rock, the more richly magnesian the olivine; the more siliceous the rock, the more ferriferous the olivine.

The end-member—**forsterite**—stands in a category by itself: it is a characteristic product of the thermal metamorphism of magnesian limestones and dolomites which contained the necessary silica in the form of detrital quartz grains, sponge spicules or tests of radiolaria. The double carbonate breaks down into calcite and magnesite, but the latter goes further and yields up CO_2 , leaving MgO (magnesia) free to combine with the silica:—



The crystals and grains of forsterite are embedded in a matrix of crystalline calcite, and the rock is termed forsterite-marble.

General Characters of the Group.

All members of the olivine group crystallize in the Orthorhombic system; but although olivine is a common mineral, well-formed crystals are rare in ordinary mineral collections. Olivine sands, formed at some points on the coasts of the oceanic volcanic islands, such as Hawaii, consist largely of singularly perfect, though small, crystals, concentrated naturally out of the olivine-basalts which form the coastline. Many of these small phenocrysts are tabular, with the pinacoid (100) well developed, combined with the vertical prism (110) and dome (101). Other characteristic crystal habits are illustrated in Fig. 11. On account of the dominance of the tabular habit noted above, in thin sections olivine tends to show six-sided cross sections of characteristic appearance (Fig. 119). In all members of the group the refractive indices are high, and strong surface relief, combined with complete absence of colour, the dominance of arcuate fractures over ill-developed cleavages,* and the strong birefringence, serve to render olivine easy to identify. The birefringence of an olivine of known composition may be read off the curve in Fig. 10; that of fayalite is very high. All olivines are prone to alteration in a distinctive manner, and in a representative collection of sections from olivine-basalts, all stages from incipient alteration to complete pseudomorphism may be studied. Commonly

* Cleavages develop parallel to the pinacoids (010) and (001) in iron-rich olivines. (See Figs. 127 and 128), notably in fayalite.

fibrous antigorite (p. 102) and/or chrysotile appear, first along the fractures, then they spread through the body of the crystal. Less ubiquitous secondary minerals formed from olivine include bowlingite, a much more strongly coloured "serpentine," yellow to reddish brown in thin section and with strong double refraction. In other rocks the olivines have been converted into ferruginous pseudomorphs, particularly where the basalts were weathered under aeolian conditions. In lamprophyres, and occasionally in other rocks, the pseudomorphs may consist largely of carbonate, with or

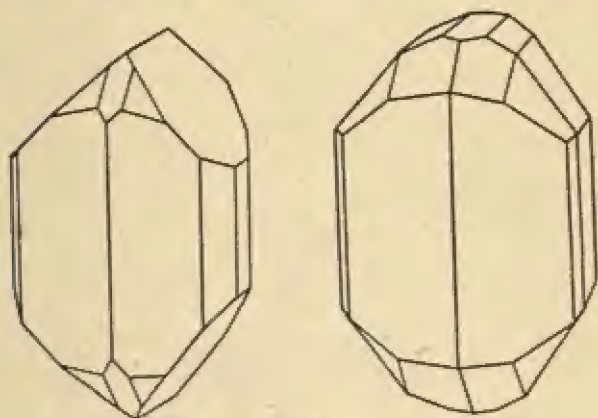


FIG. 11

Crystals of olivine.

Combination of two vertical prisms, side pinacoid, brachyprism {OkI}, macroprism {hOl} (sometimes called domes), and bipyramid.

Crystal on right from St. John, Red Sea, shows basal pinacoid in addition, also two brachyprisms and two bipyramids.

without some form of silica such as opal, chalcedony, or quartz mosaic.

Monticellite is similar to olivine in its crystallographic characters and optical orientation. It is the corresponding silicate of calcium and magnesium, with the formula CaMgSiO_4 . Under the microscope monticellite closely resembles olivine in all its optical properties except birefringence which is less than that of olivine. Its refractive indices, and therefore its surface relief, are nearly the same as those of Mg-rich olivine ($\alpha = 1.650$, $\gamma = 1.668$; with $\gamma - \alpha 0.0174$).

Monticellite is a rare mineral. It has been recorded in a peculiar type of melilite-bearing, feldspar-free lamprophyre (monticellite-alnoite) from a locality between Montreal and Ottawa, and occurs also in melanocratic olivine-nephelinite from the Swabian Alps. From experimental work on diopside-nepheline melts, N. L. Bowen has

shown that monticellite is produced (together with melilite) as a product of interaction between these two minerals.¹

Tephroite is isostructural with the olivines but is not a normal constituent of igneous rocks. It is the orthosilicate of manganese with some titanium replacing silicon and in some instances with

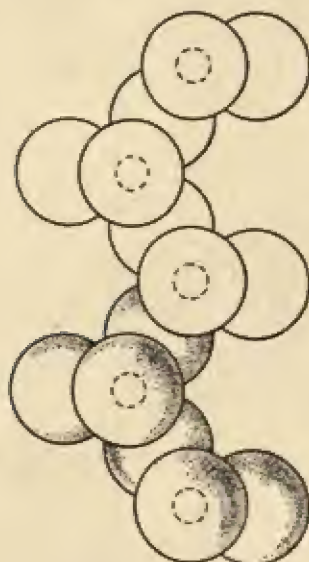


FIG. 12

Part of a chain of SiO_4 -tetrahedra, as in pyroxenes. The unit of pattern contains (Si_2O_6) shown shaded. Si-atoms shown by broken circles; large circles are O-atoms.

(OH) replacing some of the oxygen. The formula is approximately $\text{Mn}_2(\text{Si,Ti})\text{O}_4$. In this country tephroite has been discovered in the old manganese mine at Benallt in the Llyn Peninsula, North Wales.²

THE PYROXENE GROUP

The pyroxenes constitute one of the most important groups of rock-forming silicates. Compared with the olivines, they contain a higher proportion of silica to the bases present, and are thus *meta-silicates*. In different members of the group the elements iron, magnesium, calcium and sodium are present in widely varying proportions, together with smaller amounts of aluminium, manganese, titanium and lithium in some species.

¹ *Amer. Journ. Sci.*, ser. V, vol. iii (1922), p. 1.

² *Min. Mag.*, xxvii (1944), p. 33.

Atomic Structure and Chemical Relationships.

The study of the X-ray structure of the pyroxenes has shown that the fundamental SiO_4 -tetrahedra are linked together vertically into

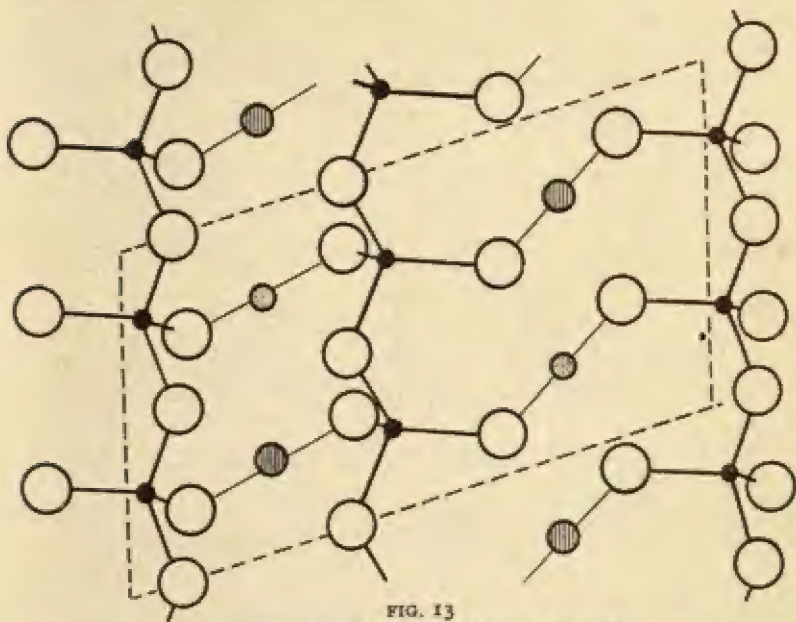


FIG. 13

Diagram showing the structure of diopside.

Portions of three parallel pyroxene chains projected on the plane (010). The unit cell is outlined, but only part of its contents are shown. Si^{'''} black; O^{''} plain; Mg^{''} stippled; Ca^{''} ruled.

chains, each tetrahedron sharing two oxygens with those immediately above and below in the chain. The individual chains are joined together through the medium of the cations, Ca^{''}, Mg^{''}, Fe^{''}, etc., which are linked to the "free" (*i.e.* not shared) oxygens. In all pyroxenes the chains run parallel to the vertical crystallographic axis, and are arranged in sheets parallel to (100). The essential features are shown diagrammatically in Figs. 12 and 13.

The form and disposition of the chains determines the positions of the cleavage planes (Fig. 14). These are parallel to the prism faces of the pyroxene crystal, and cross at a characteristic angle of 87° (or 93°).

The unit of pattern in the pyroxene chain contains Si_2O_6 . To balance the valency two Mg^{''} ions must be added, giving $\text{Mg}_2\text{Si}_2\text{O}_6$, which, of course, may be cancelled down to MgSiO_3 —magnesium metasilicate—or the mineral **enstatite**. Theoretically in **ferrosillite**

all the cations are Fe^{++} , the formula being FeSiO_3 , metasilicate of iron. Between these two extremes every gradation exists. A third essential component of the pyroxenes is the corresponding metasilicate of calcium, CaSiO_3 , which is the formula of the mineral **wollastonite**.¹ Now ignoring certain minor constituents, the composition of the pyroxenes may be represented by points on a triangle (Fig. 15),

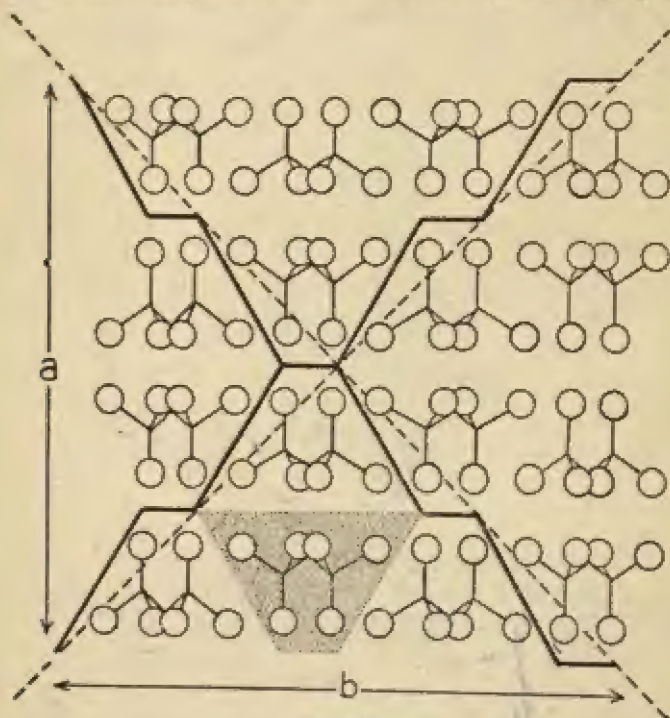


FIG. 14

Diagram showing the relationship between the atomic structure and cleavage of pyroxenes. The linked Si-O chains are shown in plan and the position occupied by one chain with its cations (not shown) is stippled. The planes of weakness are shown by heavy lines, and the resulting cleavage directions by broken lines. a and b axes shown; c is perpendicular to the paper.

similar to that used for the plagioclase feldspars (Fig. 35). The apices of the triangle represent the pure metasilicates of calcium, represented by Wo, magnesium, written En, and iron, written Fs. All

¹ Although calcium metasilicate, CaSiO_3 , here represented by Wo, is an essential component of the more complex pyroxenes, the mineral wollastonite, with the same formula, is not a pyroxene, as it has a different atomic structure. It is not a normal constituent of igneous rocks, but is characteristic of the thermal alteration of limestones. As wollastonite is like the pyroxenes, though not isomorphous with them, it has been termed a "pyroxenoid."

pyroxenes may be represented by a simple formula expressing the molecular percentages of these three components. The base of the triangle embraces all possible proportions of En to Fs, thus covering the compositional range of the important group of orthopyroxenes, and the chemically identical monoclinic equivalents. The naturally occurring members of the enstatite-ferrosilite series contain a small amount, usually between 4 and 5 per cent, of the Wo component.

The mineral **diopside** (Di), with the formula $\text{CaMgSi}_2\text{O}_6$, is represented by the point half-way between Wo and En; and similarly the analogous silicate **hedenbergite** (He), $\text{CaFeSi}_2\text{O}_6$ lies half-way between Wo and Fs. A continuously variable series links Di with He.

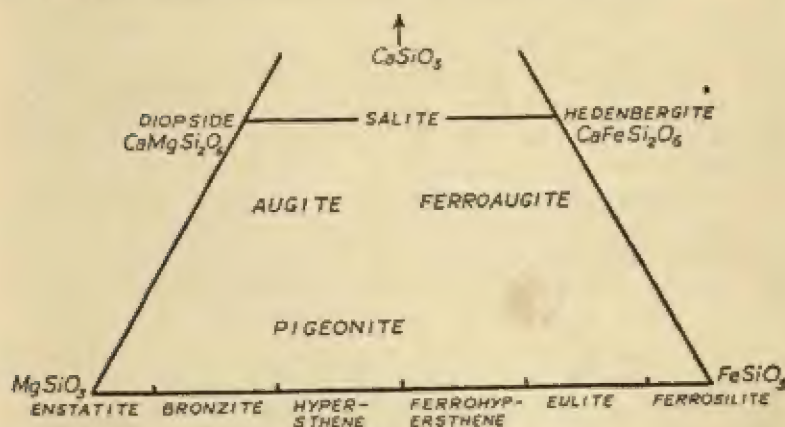


FIG. 15

Triangular diagram showing the compositional relationships between the common pyroxenes.

No pyroxenes lie above the Di-He line; but there remain some of the most important pyroxenes, which in theory go far towards bridging the gap between the diopside-hedenbergite series on the one hand, and the enstatite-ferrosilite series on the other. These are grouped as the pigeonites and the augites—both clinopyroxenes, but distinct mineral species. Pigeonites are calcium-poor; they are related in composition to the orthopyroxenes, but differ from them in containing more of the Wo component. H. H. Hess suggests a range of Wo_3 to Wo_{15} .

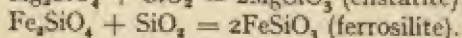
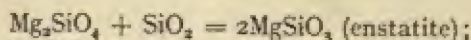
The augites lie between the pigeonites and the diopside-hedenbergite series. The most important component not shown on the triangle is alumina, a moderate amount of which is present in both augites and pigeonites.

(1) ORTHOPYROXENES: THE ENSTATITE-FERROSILITE SERIES

In the past several names have been applied to different members of the series, but they have been used in more than one sense. There is much to be said for erecting arbitrary divisions at the same molecular percentages as those used in the olivine and plagioclase groups; i.e. at 10, 30, 50, 70 and 90. This involves the recognition of six mineral species in the series,¹ the names and ranges of composition of which are shown in Fig. 15.

The conditions controlling the crystallization of the enstatite-ferrosilite series have been studied by Bowen and Schairer,² who have shown that pyroxenes within this range of composition may occur in two forms, one orthorhombic, the other monoclinic. The monoclinic forms are known by the same names as the orthorhombic ones, with the prefix clino-: thus clino-enstatite, clinoferrosilite, etc. The monoclinic forms are high-temperature minerals, produced under laboratory conditions, and occur also in some meteorites. On the other hand, the orthorhombic forms are low-temperature minerals and the more magnesian members are widely distributed in igneous rocks. Ferrohypersthene is relatively rare, eulite is practically restricted to a peculiar group of rocks (eulysites), while ferrosilite is exceedingly rare: it has been recorded from small geodes in rhyolitic obsidian.³ It is significant that the most ferriferous pyroxene occurs in the same kind of rock as the corresponding member of the olivine group, fayalite. Similarly, orthopyroxenes which crystallize at high temperatures are richer in Mg than those which separate at lower temperatures. Therefore as we pass from more basic to more acid rocks, the pyroxene changes from magnesium-rich to iron-rich.

The general similarity between the members of the olivine group and the orthopyroxenes will have been noted: both contain the same elements, but in different proportions. The addition of silica to any member of the olivine group converts it into the corresponding orthopyroxene: thus forsterite with additional silica yields enstatite; fayalite with silica gives ferrosilite:—



Similarly it is known from the results of experiments that an orthopyroxene melts incongruently into the corresponding olivine, with the liberation of silica; conversely, on cooling a basic magma

¹ Poldervaart, A., "The Relationship of Orthopyroxene to Pigeonite," *Min. Mag.* xxviii (1947), p. 164.

² "The System MgO-FeO-SiO₂," *Amer. Journ. Sci.*, xxix (1935), p. 151.

³ Bowen, N. L., "Ferrosilite as a Natural Mineral," *Amer. Journ. Sci.*, xxx (1935), p. 481.

containing the essential components of an orthopyroxene, the first crystals to form are olivine (see p. 172).

The rôle of orthopyroxenes as rock-formers is an important one. As they are all stable in the presence of silica, they occur in rocks covering a wider silica range than is the case with the olivines. Thus hypersthene is found in the "acid" hypersthene-granite, charnockite, in the "intermediate" hypersthene-diorite; it is best known, perhaps, in the "basic" hypersthene-gabbros and norites, while the ultramafic rocks include nearly monomineralic types such as bronzitites, etc. In the fine-grained categories, the orthopyroxenes are best developed in the andesites; while in the medium-grained "dyke-rocks," hypersthene is characteristic of certain types of dolerite, particularly those which are quartz-bearing.

A special characteristic of much of the hypersthene and bronzite of the coarser-grained igneous rocks of basic composition is the clear evidence they afford of the inversion of these minerals from pigeonite. The orthopyroxene in these cases exhibits regularly orientated inclusions of clinopyroxene, in coarse-grained rocks arranged as sheets parallel to (100) in the more magnesian, and parallel to (001) in the iron-rich types.¹ These orthopyroxenes with regularly orientated sheet-inclusions of clinopyroxene are chemically equivalent to pigeonite, and the phenomenon is a striking example of exsolution.

(2) CLINOPYROXENES.

(a) **The Diopside-Hedenbergite Series.**—As noted above, this series is continuously variable between the two end-members, and with decrease in the Wo component, they grade down into the augites: the division between the two series is quite arbitrary, and may be drawn, following Hess,² at Wo₄₅. Typically the members of the series occur in metamorphic rocks: typical diopside is found in skarns and other metamorphosed limestones; but augites near to diopside in composition are characteristic of the less basic igneous rocks, particularly the fine-grained acid and intermediate lavas of the rhyolite-trachyte range. Hedenbergite, too, is rare in igneous rocks, judging by recorded occurrences, but hedenbergite-granophyre, a thoroughly acid rock, has been described from Greenland.³ With increasing iron content diopside passes into salite⁴ and ferrosalite, and ultimately, of course, into hedenbergite.

¹ Henry, N. F. M., "Lamellar Structures in Orthopyroxenes," *Min. Mag.*, xxvi (1942), p. 179.

² Hess, H. H., "Pyroxenes of the Common Mafic Magmas," *Amer. Min.*, xxvi (1941), pp. 515-535 and 573-594. Also *Amer. Min.*, xxxiv (1949), p. 621.

³ Wager, L. R. and Deer, W. A., "The Petrology of the Skaergaard Intrusion," *Medd. om Grønland*, Bd. 105, Nr. 4 (1939), p. 209.

(b) **Pigeonites.**—Pigeonites are so named from the lavas of Pigeon Point, Minnesota, which contain a pyroxene of this type. Formerly they were known as "enstatite-augites." They are essentially components of andesitic and basaltic lavas or dyke rocks: they are not found in coarse-grained, slowly-cooled rocks, for under these conditions pigeonites are unstable, and invert into orthopyroxenes with exsolved inclusions of augite. In rapidly-cooled rocks, however, pigeonite may persist indefinitely in a metastable condition. Occasionally there may be a slight colour difference between pigeonite and augite in the same rock, but in general the distinction is not

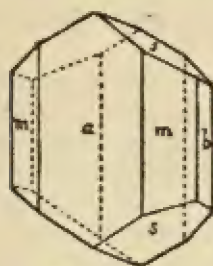


FIG. 16

Crystal of augite.

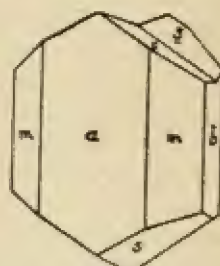


FIG. 17

Crystal of augite twinned on {100}.

- a Orthopinacoid (100).
 - b Clinopinacoid (010).
 - m Prism (110).
 - s Hemi-bipyramid (111).
- (After Rosenbusch.)

easily made, and is best left to the expert. Measurement of the optic axial angle, involving the use of universal stage, and the determination of the position of the optic axial plane, are involved. For augites the latter is always parallel to (010); but in pigeonites it is normally perpendicular to the plane of crystallographic symmetry.

(c) **Augites.**—Augite certainly holds the centre of the stage so far as the student is concerned. In one form or another it is by far the most widely distributed pyroxene. The familiar black augites, as shown in Figs. 16 and 17, are among the best known monoclinic crystals available for study. As a component of the more basic igneous rocks augites are ubiquitous, and are especially characteristic of basalts, dolerites and gabbros. Common augite has an average composition represented by $\text{Wo}_{40}\text{En}_{45}\text{Fs}_{15}$, and is of the type seen in countless doleritic and gabbroic rocks. But there are at least two

* It must be noted that salite was formerly applied to a pyroxene showing a basal striation—the so-called salite or sahlite-structure; but following Hess and others, is here used as a specific mineral name.

important variants: one containing appreciable amounts of titanium—this is **titanaugite**, and the other is a sodic variety, grading into aegirine (see below) and therefore termed **aegirine-augite**. Both are distinctive in thin section. Titanaugite, which is characteristic of somewhat alkaline basic igneous rocks, is mauve to lilac-brown, slightly pleochroic and exhibits strong dispersion. Aegirine-augite is superficially like aegirine in colour, being bright green and distinctly pleochroic, but has the characteristic widely oblique extinction of common augite. Like aegirine itself, aegirine-augite is found in alkaline igneous rocks and is often associated with such strongly sodic minerals as nepheline and sodalite.

(d) **Aegirine** and **acmite**¹ are essentially the same in chemical composition, which may be represented by the formula, $\text{NaFe}^{III}\text{Si}_2\text{O}_6$. In hand specimens they occur as black lustrous prisms, sharply pointed in acmite. While in thin sections they exhibit the general properties of augite, they differ in sign (aegirine, negative; augite, positive); in the size of the extinction angle (see Fig. 18); and in being distinctly pleochroic. Typically for aegirine the scheme is:—

X, bright grass green;

Y, greenish yellow;

Z, brownish yellow.

Acmite, by contrast, is brown in thin section.

Confirmation of the diagnosis is afforded by the small maximum extinction angle, about 5° .

Optical Orientation.

In all pyroxenes but one the optical plane of symmetry coincides with that of crystallographic symmetry, *i.e.* parallel to (010). In pigeonite it appears to be perpendicular to the (010) plane. It follows that the maximum angle of extinction will be read in the (010) section, and this angle provides a ready means of finding the approximate composition of a pyroxene in thin section. Schematically these angles are set out in Fig. 18. The angles marked in the corners of the "fans" to the left of the middle line are those between the slow vibration (Z) and the cleavage traces. The complementary angles, between the fast direction (X) and the cleavage-traces are, of course, found by subtraction from 90° . Certain confirmatory observations have already been mentioned for specific minerals. Some general points require notice. The distinction between orthopyroxene and clinopyroxene in thin section is not always easy. In general two criteria are relied upon: the extinction and the birefringence. It is commonly stated that sections of orthopyroxene (or any

¹ Sabine, P. A., *Min. Mag.*, **xxix** (1950), p. 123.

orthorhombic mineral), must show straight extinction; while augite (or any other monoclinic mineral) must extinguish obliquely. Neither statement is wholly true. Sections of orthopyroxene show straight extinction when, and only when, they lie in a principal zone: *i.e.* such sections as those parallel to (100), (010), (110), etc.; but a "skew" section cut parallel to a bipyramid face, for example, will show oblique extinction at possibly a wide angle. On the other hand, a section of clinopyroxene will show straight extinction to the prismatic cleavage-traces in a (100) section; but it will show oblique extinction, as noted above, at the widest angle, in the (010) section.

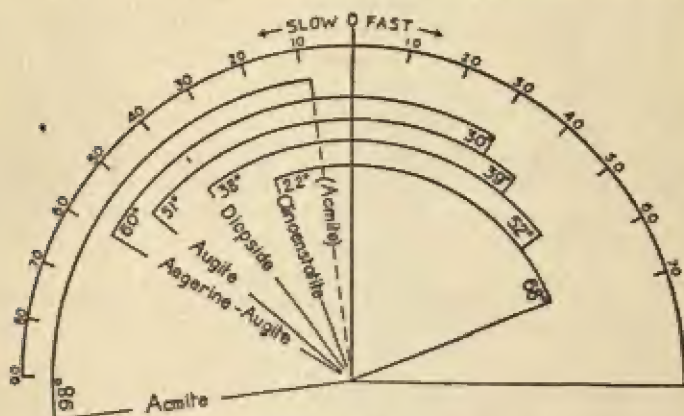


FIG. 18

Diagram of the extinction angles in monoclinic pyroxenes in sections parallel to the side-pinacoid (010). The vertical line (O) represents the vertical cross-wire; the sides of the fans correspond to the cleavage traces on (010) sections in the extinction positions.

Symmetrical extinction is exhibited by the section perpendicular to the cleavage planes. All three cases are illustrated in Fig. 19.

As regards birefringence, that of the orthopyroxenes is uniformly weak, and grey interference colours are characteristic. But certain sections of clinopyroxene will exhibit the same colour between crossed nicols, if they happen to be cut nearly perpendicular to one of the optic axes. It follows that it would be unwise to record the presence of orthopyroxene in a rock containing augite, on the evidence of grey interference colours or straight extinction alone; one such section lying in the company of others showing oblique extinction and the characteristic yellow, red, purple or blue of augite, should be viewed with suspicion—it is probably augite too.

The distinction of enstatite from bronzite and hypersthene depends upon the exact measurement of certain of the optical char-

acters, particularly the size of $2V$, and the orientation of the indices. It is customary to refer to as hypersthene any orthopyroxene which is pleochroic; but too much must not be expected. The colours shown

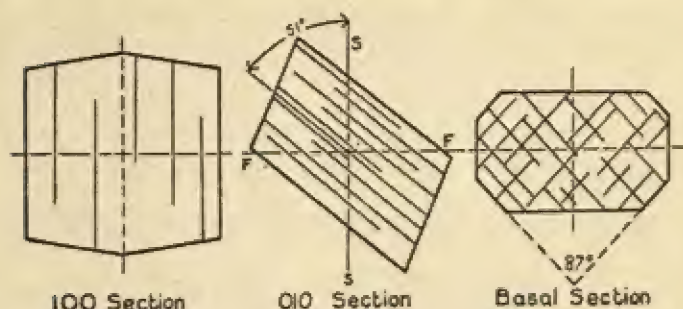


FIG. 19

Sections through an augite crystal drawn in the extinction positions. SS—slow vibration; FF—fast vibration direction. The (100) section extinguishes straight; the basal section, symmetrically; and the (010) section obliquely at the maximum angle.

are very anaemic, and rather like those exhibited by andalusite—from watery pale bluish green to equally light pink.

As most of the pyroxenes are members of continuously variable series, zoning is common. Some titanaugites in particular are note-

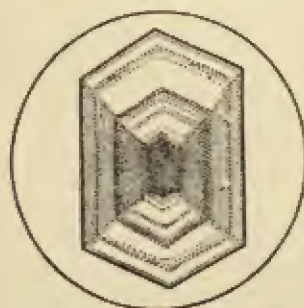


FIG. 20

Zoning and hour-glass structure in augite in lamprophyre, Mühlörzen, Mittelgebirge, Bohemia.

worthy on this account, particularly when examined near extinction between crossed nicols. Hour-glass structure (Fig. 20) is a kindred phenomenon which results from the selective adsorption of ions by different faces during growth. The combination of hour-glass struc-

ture with zoning gives some of the most striking colour effects to be seen in rock sections.

THE AMPHIBOLE GROUP

The amphiboles form a large group of complex metasilicates, and are chemically related to the pyroxenes. Any species of pyroxene

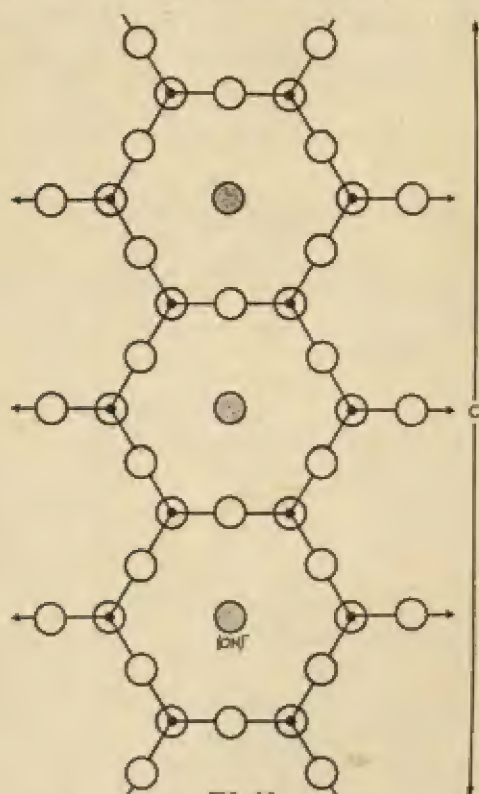


FIG. 21

Diagram of the atomic structure of the amphiboles: the amphibole "band." The arrows indicate the linkage of "free" oxygen atoms to cations. The oxygens superimposed on the Si atoms are similarly linked to cations, thus isolating each Si-O band from its neighbours.

may contain identically the same elements as the corresponding amphibole, but they are present in different proportions; while a more fundamental difference is the presence in the latter of hydroxyl, represented by (OH), and with a negative charge of one unit. A hydroxyl group is the same size, and functions in the same way, as an oxygen atom.

(1) *Chemical Relationships.*

The X-ray structure consists fundamentally of "bands" of linked SiO_4 -tetrahedra. Each band in effect consists of two pyroxene chains united by shared oxygens as shown in Figs. 21 and 22. The arrangement of the bands parallel to the vertical axis, is essentially the same as for the pyroxene chains, illustrated in Fig. 14.

The unit of pattern in Fig. 21 contains Si_4O_{11} ; but to avoid the necessity of splitting an atom, it is convenient to double this. Each of these Si_8O_{22} units is associated with two hydroxyls (OH). Thus the total negative electrostatic charge on the unit is 46, while this is partly counterbalanced by the positive charge which amounts to 32, due to the silicons. The negative residual charge of 14 units must be

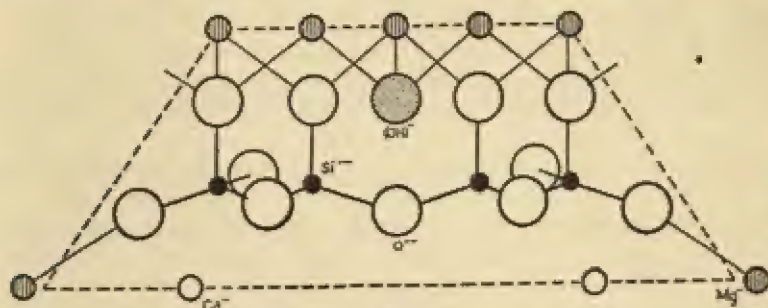


FIG. 22

Diagram of end view of the amphibole band. B-axis, left to right; C-axis at right angles to the paper. The two Mg atoms outside the boundary of the band belong to adjacent bands immediately left and right of the one illustrated. Only some of the bonds are represented.

balanced out by the addition of the requisite number of cations. The latter are the same as those occurring in the pyroxenes, *i.e.*, Mg'' , Fe'' and Ca'' . If all the necessary cations are Mg'' , the formula becomes $(\text{OH})_2\text{Mg}_5\text{Si}_8\text{O}_{22}$, which represents the composition of the amphibole kupfferite, equivalent to enstatite. Similarly $(\text{OH})_2\text{Fe}_7\text{Si}_8\text{O}_{22}$ is grunerite, a monoclinic amphibole formed under metamorphic conditions, and equivalent to the pyroxene clinoferrosilite. These two end-members are connected by anthophyllite (orthorhombic) and cummingtonite (monoclinic), with a variable ratio of Mg to Fe, and thus corresponding to the En-Fs range of pyroxenes (bronzite, hypersthene and eulite). It has not been found necessary to subdivide the Mg-Fe amphiboles in the same way as the pyroxenes, as they have not the same importance in igneous rocks as the latter. The amphibole equivalent to diopside is tremolite, which contains both calcium and magnesium, in the proportion of 2 to 5: thus—

$(\text{OH})_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}$. As Fe'' replaces some of the Mg'' in this formula, tremolite gives place to actinolite, which is thus similar to the salite-hedenbergite range.

The commonest, and by far the most widespread, amphibole is hornblende, the equivalent of augite among the pyroxenes. Like the latter, hornblende is of extremely complex composition. For this reason it is not appropriate to quote a specific formula.

If, in the formula for tremolite, we substitute $\text{Na}'\text{Fe}'''$ for $\text{Ca}''\text{Mg}''$, the amphibole, riebeckite, is derived. This is closely comparable with aegirine and is the most widely distributed of the sodic amphiboles. The formula may be written $\text{Na}_2\text{Fe}_2'''\text{Fe}_3''\text{Si}_8\text{O}_{22}(\text{OH})_2$. Similarly in the latter, $\text{Mg}''\text{Al}'''$ may be substituted for $\text{Fe}''\text{Fe}'''$, giving glaucophane, $\text{Na}_2\text{Al}_2\text{Mg}_3\text{Si}_8\text{O}_{22}(\text{OH})_2$, a mineral foreign to igneous rocks, but occurring in glaucophane-schists, formed by metamorphism from strongly sodic rocks of the spilite type. Glaucophane grades into riebeckite, and natural specimens usually have a composition between the two extremes. Allied closely to these amphiboles are barkevikite and arfvedsonite, both types rich in sodium and ferrous iron.

One further type of substitution must be noted. In pargasite, an amphibole typical of altered limestones, some of the silicon atoms have been replaced in the structure by aluminium so that in place of Si_8 , the grouping (Al_2Si_6) occurs. A readjustment of the valency is necessary, of course, and this is effected by the addition of Na' . Thus the complete formula becomes $\text{NaCa}_2(\text{Mg}_4\text{Al})(\text{Al}_2\text{Si}_6)\text{O}_{22}(\text{OH})_2$. Finally, a kindred type is hastingsite, found in alkali-rich igneous rocks. A recent analysis shows the formula of one particular specimen to be:— $(\text{Na},\text{K})_2\text{Ca}(\text{Mg},\text{Fe}''',\text{Fe}'',\text{Al},\text{Ti})_3(\text{Al},\text{Si})_8(\text{OH})_2\text{O}_{22}$. This is a formidable-looking formula, but merely stresses the possibility of further atomic substitutions, controlled, of course, by the necessity of balancing the valency, and by the availability of the appropriate spaces in the atomic structure.

(2) *Optical Orientation.*

In all but one rare type, the optical orientation of the amphiboles is the same as that of the pyroxenes: the optic axial plane lies parallel to (010). The details of extinction in variously orientated sections considered above in relation to the pyroxenes, apply equally to the amphiboles. The significant facts are illustrated in Fig. 23. The most obvious means of differentiating between the several members of the group is the size of the extinction angle in (010) sections, as indicated in Fig. 24. The angles read to the left of the middle line are those between the slow vibration direction (Z) and the cleavage traces which mark out the position of the vertical axis.

Similarly, those to the right, marked "fast" on the diagram, are measured between the fast vibration direction (X), and the cleavage traces. The significant point here is that while riebeckite and

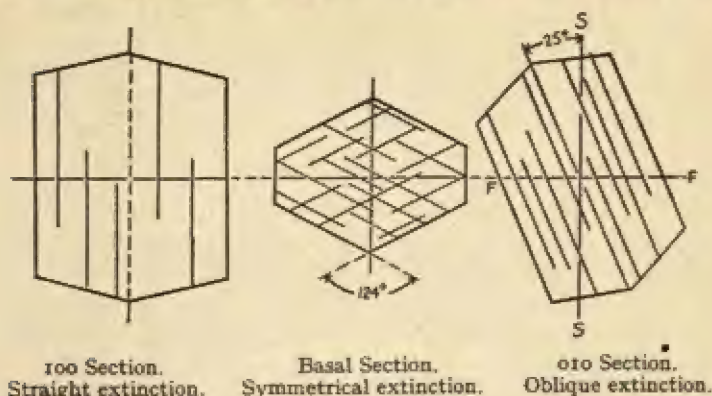


FIG. 23

Sections through a crystal of hornblende, showing prismatic cleavage traces and drawn in positions of extinction. SS—slow vibration, FF—fast vibration.

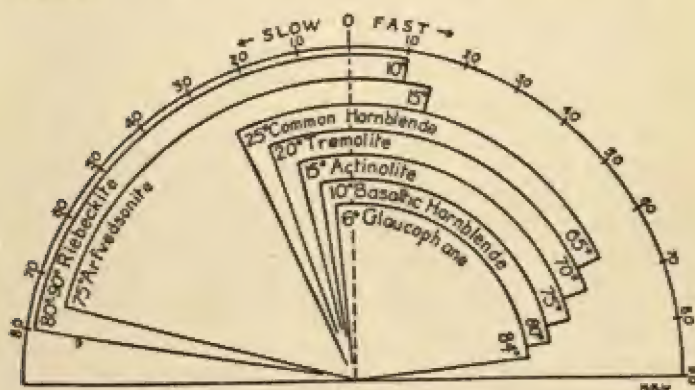


FIG. 24

Diagram showing extinction positions of the amphiboles. The figures in the left-hand top corner of each 90°-fan are the maximum extinction angles shown by (010) sections. The vertical line marked "O" represents the vertical cross-wire in the eye-piece of the microscope. The sides of the fans mark the positions of the cleavage traces in 010 sections in the extinction position.

glaucophane both have much the same extinction angle, in the former the extinction position nearest to the cleavage traces is the fast vibration, but with the latter it is the slow direction.

(3) *Specific Characters.*

Cummingstonite, the monoclinic amphibole equivalent in composition to the orthorhombic pyroxene, hypersthene, may be represented by the formula, $H_2(Mg,Fe)_7Si_8O_{22}$. It is not a common mineral and is usually metamorphic, though it is sometimes seen replacing hypersthene and olivine in basic igneous rocks. It also occurs in corona structures (Fig. 118) in these rocks.

Tremolite is a common constituent of metamorphosed limestones, in which it occurs in lamellar or bladed white lustrous crystals. It occurs also in some serpentinites that have been formed by metamorphism of ultrabasic rocks. In thin section tremolite resembles hornblende in general characters, but is quite colourless. In certain occurrences it is acicular to finely fibrous, and is one of the forms of commercial asbestos.

Actinolite is most familiar in the form of deep green to light green elongated prisms or acicular aggregates in schistose rocks; but it is also a common mineral in thin sections of basic igneous rocks, in which it has formed at the expense of clinopyroxene. It is easily recognized by its pleochroism in shades of green, its extinction features and moderately strong birefringence (0.025).

Hornblende is well represented in mineral collections by black crystals of prismatic habit of the type illustrated in Figs. 25 and 26. The side pinacoid is sometimes suppressed, otherwise there is little significant variation in crystal habit. Twinning on (100), which may be simple or repeated, is common (Fig. 26). On account of the wide variation in chemical composition of different specimens, some difficulty is experienced in giving a general statement of the optical characters; but the absorption formula is normally Z greater than Y, greater than X, with X a light shade of yellow or yellowish green; Z deep green, often olive-green, while Y is an intermediate light green. The presence of the "glaucophane molecule" introduces blue into the colour scheme. The birefringence (about 0.022) is such as to give 2nd order green or yellow; but sections lying in other positions may show little perceptible change on crossing the nicols.

Pargasite very closely resembles common hornblende into which it grades, and the best indication of its identity is its associates: it occurs with bright green diopside and other lime-rich silicates in a matrix of crystalline calcite, for example in the Tíree Marble,¹ in the Hebrides.

¹ Hallimond, A. F., "Pyroxenes, Amphibole and Mica from the Tíree Marble." *Min. Mag.*, xxviii (1947), p. 230.

Riebeckite.—Megascopically riebeckite closely resembles common hornblende, but under the microscope it is very distinctive. The colour is dull bluish green, and the absorption is so strong in some varieties that it appears nearly black. In less extreme cases the X vibration is deep indigo blue, Y is dull blue to brownish or yellowish green in different cases, while Z is generally greenish, but may be nearly black. The birefringence is weak (0.004), so that in

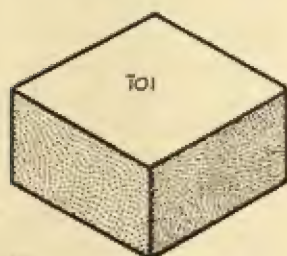


FIG. 25

The two ends of a simple crystal of hornblende, in plan. The forms represented are: clinoprism $\{011\}$ and hemiorthodome $\{101\}$. The forms in the vertical zone are: prism $\{110\}$ and side (clino-) prism $\{010\}$.

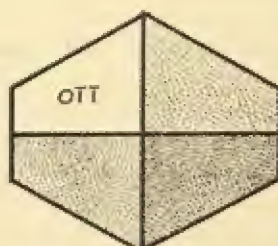
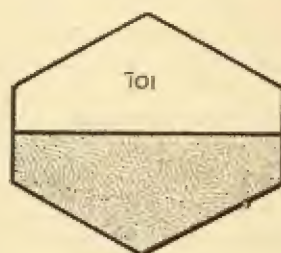


FIG. 26

The ends of a simple hornblende twin, in plan. The upper figure shows the hemiorthodome faces; the lower, the clinoprism (or clinodome) faces. The twin-plane is (100).

consequence of the strong absorption, there is little change of colour on crossing the nicols. Riebeckite is characteristic of strongly sodic acid igneous rocks: riebeckite-granite, microgranite and rhyolite have been described, the riebeckite-microgranites of Mynydd Mawr in North Wales (Fig. 91), and Ailsa Craig in the Firth of Clyde (Fig. 90) being good examples. In these rocks the riebeckite has a distinctive mode of occurrence: it forms micropoikilitic "mossy" patches in which the other components are embedded.

Glaucophane.—None of the amphiboles is more strikingly pleochroic than glaucophane. In its most typical form it exhibits the

following:—X, colourless to light yellow; Y, violet and Z, pure Prussian blue. Thus, at their best riebeckite and glaucophane are very distinctive; but as they grade into one another, cases may arise where the diagnosis must be checked, for example, by the sign of the elongation (riebeckite being length—fast, and glaucophane length—slow).

Barkevikite has been recorded from a number of British and foreign alkali-rich rocks, for example, those occurring in the Lugar sill in Ayrshire. Again the pleochroism scheme is very distinctive, with X clear light yellow, Y strong red-brown and Z dark brown. The absorption formula is on the usual hornblende plan, with X the least, and Z the most strongly absorbed. Care has to be exercised in distinguishing between barkevikite and lamprobolite, which until recently was called basaltic hornblende. They are closely similar as regards pleochroism, absorption, extinction, position of the optic axial plane, parallel to (010), and refractive indices; but differ in birefringence, basaltic hornblende (0.068) being distinctly higher than barkevikite (0.021) in this respect. There is need here for a lot more information.

Lamprobolite (basaltic hornblende): see preceding paragraph. This amphibole, which is brown in thin section, has been recorded from many different types of rock, but is dependent for its characters not so much on the kind of magma from which it crystallized, as on the conditions to which it was subjected subsequently. This is suggested by the fact that common hornblende can be converted experimentally into lamprobolite by heating, which has the effect of changing the state of oxidation of the iron, and of breaking down the hydroxyl.

Arfvedsonite is related chemically to barkevikite and occurs frequently in strongly sodic syenitic rocks such as sodalite-syenite and nepheline-syenite. It is very deeply coloured in thin section, a rich dark green, but differs from most other amphiboles in that the Z-vibration is the least absorbed. Further, arfvedsonite has negative elongation, the fast vibration, X, lying 15° or less from the cleavage traces.

Hastingsite is yet another alkali-rich aluminous amphibole occurring typically in nepheline-syenites (Ontario), theralites (Crazy Mts., Mont.), etc. In its optical characters it approaches closely to pargasite and even common hornblende, but sections tend to be rich bluish-green in the position of maximum absorption. The extinction angle is a few degrees larger than that of hornblende; but the most distinctive feature is the very small optic axial angle. Thus, given a suitably orientated section, the identification of hastingsite, suggested by its associates, is readily confirmed.

(4) Conditions of Formation and Distribution in Rocks.

Because of their complex composition and of the practical difficulties that arise, the conditions of crystallization of the amphiboles have not been studied experimentally as in the case of the olivines and pyroxenes. However, it is possible to infer a great deal from the study of thin sections of rocks. It might be anticipated from the facts of their chemical composition that amphiboles are characteristic products of crystallization of a "wet" magma. They require a certain flux concentration for their development. This is achieved in magmas at relatively low temperatures only after considerable crystallization of anhydrous silicates has taken place. Thus amphiboles follow pyroxenes: they may be moulded upon crystals of the latter, or they may show a replacive relationship.

The close chemical and structural similarity between the two groups results in particularly easy replacement of another kind. Under conditions of low-grade metamorphism pyroxene may be altered into an amphibole of appropriate composition, and usually of fibrous habit. This is the first stage in the conversion of a pyroxene-bearing basic rock into a hornblende-schist or amphibolite.

The reverse relationship may also be observed. Large euhedral hornblendes occurring in andesitic lavas may show all stages of conversion into granular pyroxene due to a temporary rise in the temperature of the lava.

Common hornblende is characteristic of plutonic rocks, especially the acid and intermediate granodiorites, diorites and syenites. In the finer grained and more quickly cooled equivalents of these same rocks, the mineral assemblage has normally crystallized at a higher temperature, so that amphiboles are less common and may be absent. In alkali-rich igneous rocks such as nepheline-syenites, phonolites, etc., the special iron-rich, sodic types including primarily riebeckite, and less commonly hastingsite, barkevikite and arfvedsonite, are widespread. Amphiboles are uncommon in basaltic rocks, but when they do occur, they are found to be Mg-rich, thus falling into line with the olivine and pyroxene groups.

THE MICA GROUP

The micas constitute one of the most important groups of mineral silicates which are chemically distinct from the groups so far considered in two respects: the alkali elements are important in all micas; but unlike certain amphiboles and pyroxenes, calcium is absent. In atomic structure, too, they are distinctive. The atoms are arranged in extended sheets as discussed below.

Atomic Structure and Chemical Relations.

In micas and in several other groups of minerals built on the same plan, the SiO_4 -tetrahedra are linked to one another at three corners, and thus form indefinitely extended sheets in which the atoms of

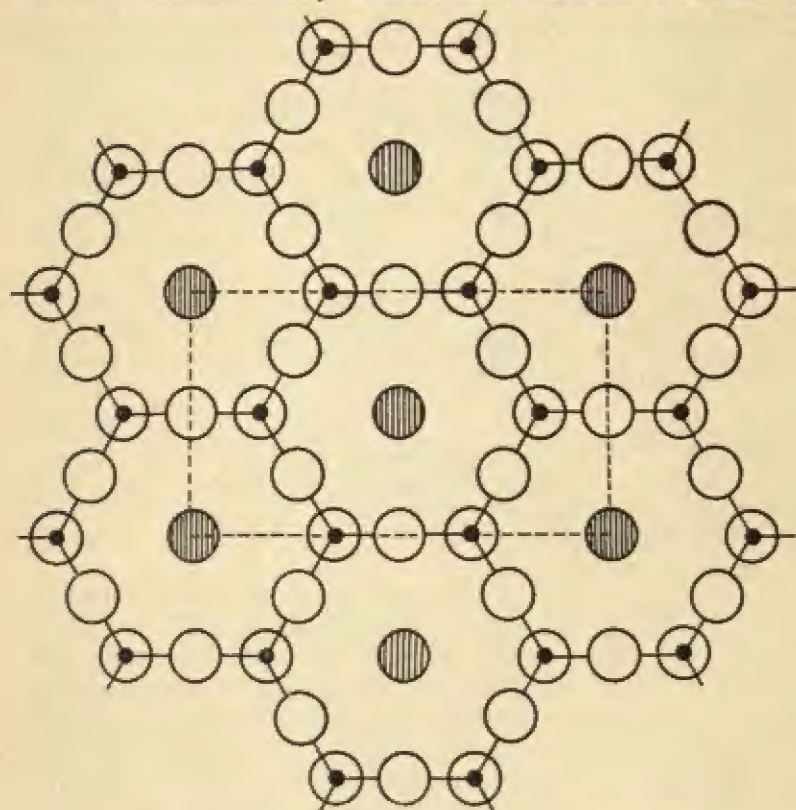


FIG. 27

Diagram showing the extended sheet structure of the micas.

Si atoms, black; O- atoms, white; hydroxyl (OH), ruled. The characteristic double sheet—the thinnest possible cleavage flake—comprises two of those illustrated, in mirror-image relationship (see Fig. 28).

different kinds are arranged on a hexagonal plan (Fig. 27). The unit of pattern contains Si_4O_{10} , but as with the amphiboles, to avoid having to deal with half atoms, it is convenient to double this. The essential hydroxyl groups are included in the planes containing the "free" oxygens in the tetrahedra, and four of these are associated with each unit.

In micas a certain degree of substitution of silicon by aluminium is possible. These Al^{+++} atoms which function as silicons are "proxy

Al's," and each unit contains two of these. Thus the "standard formula" is $(\text{OH})_4(\text{Al}_2\text{Si}_6)\text{O}_{20}$. There is a considerable residual negative charge on this unit which is balanced out by the addition of atoms of sodium and potassium, together with Al, Mg, and Fe in

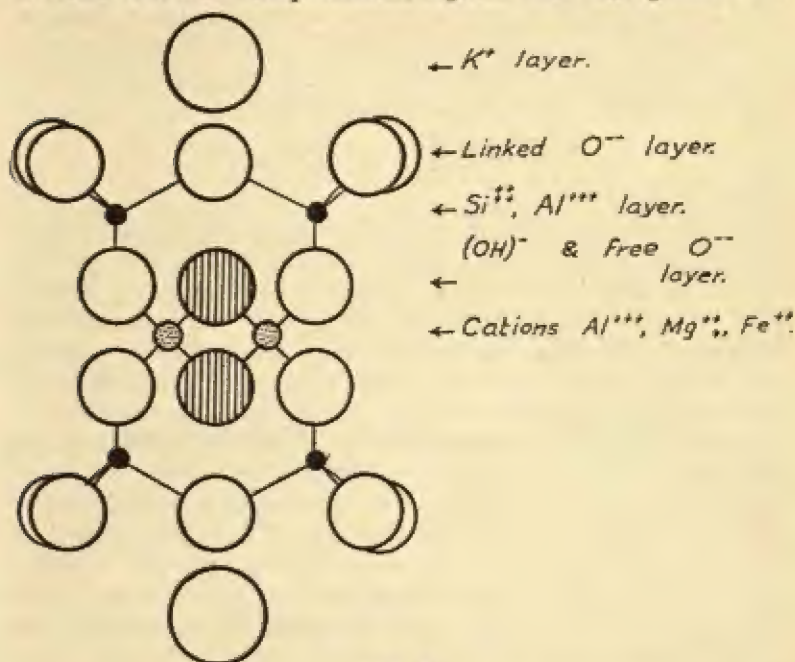
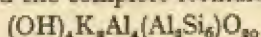


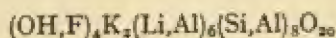
FIG. 28

Diagram showing the order of atomic layers in mica: section through the double sheet.

different cases. Thus in muscovite, one of the commonest micas, K and Al are so used, and the complete formula is:—



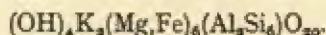
Actually a slight substitution of Al by Fe takes place in some muscovites, in which case $(\text{Al}, \text{Fe}^{3+})_4$ may be substituted for Al_4 in the formula. Lepidolite is the best known "lithia-mica," but although repeatedly analysed, it has proved exceedingly difficult to express the composition in a simple formula. The following is an approximation:



with Li varying from one to four atoms, with corresponding adjustments in the Al, Si ratio.

Zinnwaldite is another lithia-mica, similar in general composition to the above, but with Fe^{2+} replacing some of the Al.

If in the formula of muscovite Mg_6 replaces Al_3 , the formula of phlogopite is obtained: $(OH)_4K_2Mg_6(Al_2Si_4)O_{20}$. This is often spoken of as the "magnesian mica." By comparison muscovite is the "aluminous mica," not the "potash mica," as it is so commonly called, for it contains neither more nor less potash than phlogopite or, indeed, than biotite. The latter is the common ferro-magnesian mica, and is of very complex composition. A first approximation to its composition is suggested by the following:—



General Properties.

As a direct consequence of their atomic structure the micas show pseudohexagonal symmetry, though actually they are monoclinic. To the eye they appear to be simple hexagonal crystals of tabular habit; but careful measurement shows that the basal pinacoid is not perfectly at right angles to the prism faces. The angle beta is within a few minutes of 90° however; and similarly the angles between the apparent hexagonal prism faces are nearly, but not exactly, 60° . Occasionally crystals are found which show hemibipyramid and other faces which betray the true symmetry of the mineral: otherwise the percussion figure obtained by smartly tapping a centre-punch placed in contact with the (001) face of the mica, proves that the symmetry is not hexagonal. A six-rayed star is produced in this way, but the rays are not identical: two, which lie in the single plane of symmetry, are more strongly developed than the others. This fulfils another useful purpose, as it serves as a guide when finding the position of the optic axial plane.

The most striking physical property of all micas is the perfect basal cleavage, which takes place between the pairs of sheets of SiO_4 -tetrahedra, and in the planes of alkali atoms (Fig. 28). Not only are the atoms fewest in these planes, but the K atoms are very loosely bonded to the rest of the structure.

Twinning is not uncommon in micas, on the so-called "mica law," in which the twin plane is approximately coincident with (110), while the composition plane may be either (001) or (110). In the latter case the basal cleavages of both parts of the twin are coincident, but on account of the different orientation of the two parts, there is a striking difference in absorption, best seen when looking obliquely through a cleavage plate towards a good light. Twinning is seldom seen in thin sections.

Optical Orientation.

Although the pseudohexagonal symmetry of the mica crystal has been stressed above, examination of its optical properties imme-

diately demonstrates that it is not hexagonal. As a group the micas are biaxial, though the size of $2V$ is very variable, and the optic axial plane in some cases is parallel, but in others perpendicular, to (010), (see Fig. 29). This difference in orientation is the basis of the division of the micas into two groups, which essentially comprise the light and the dark micas respectively. In all micas the fast vibration X is perpendicular to the (001) plane, and as X is the acute bisectrix, all micas are optically negative.

THE LIGHT MICAS

(a) **Muscovite** is the silvery white mica seen in hand specimens of many granites, particularly the strongly potassic varieties, and in the pegmatites and minor intrusives associated with them. In

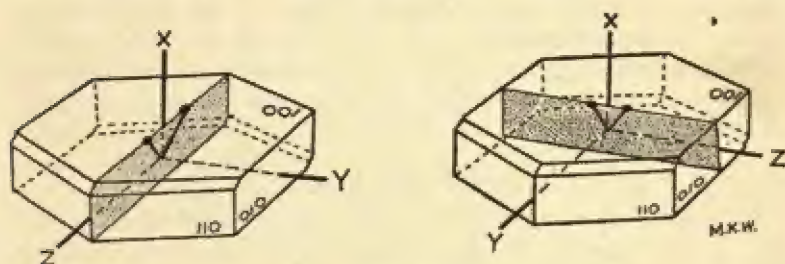


FIG. 29

Diagram showing the optical orientation of the micas. *Left*, the biotite-phlogopite series; *right*, the light micas.

igneous rocks it is restricted to the most highly silicated types. It is also widely distributed in schists and gneisses.

Muscovite originates in another way, however. The potassic feldspars contain the same elements as muscovite, and are readily converted into the latter as a consequence of hydrolysis. Conversely, when rocks or even sediments containing white mica suffer thermal metamorphism, the mica is converted into orthoclase. A distinction is drawn between primary white mica formed by crystallization from a melt, and the secondary white mica produced by the alteration of potash-rich silicates. The latter type is **sericite**. Although identical in composition with muscovite, sericite has an entirely different mode of occurrence in rocks, and there appear also to be slight physical differences. The sericite usually occurs in the form of aggregates of minute flakes. Soda-rich feldspars including albite may be crowded with such mica flakes, and this is believed to be a distinct species, known as **paragonite**, analogous in composition with muscovite but with Na substituted for K in the formula.

Optically muscovite is distinctive chiefly by reason of its strong birefringence—0.036. This ensures that most vertical sections show brilliant interference colours; but the basal section polarizes in light grey, and as the distinctive perfect cleavage traces are absent, it may easily be misidentified by the unwary. Such sections exhibit a perfect biaxial interference figure, however, on which the sign is easily checked.

(b) **Lepidolite**, a lithium-bearing light mica, is attractively coloured lilac in the mass, and although large crystals a foot or more across are obtained from certain complex pegmatites, a more usual mode of occurrence is in the form of aggregates of flakes or scales, as the name implies. Some particularly attractive mineral specimens consist of lepidotite acting as matrix to brightly coloured lithium tourmalines. Although the general optical orientation is the same as for muscovite, the angle $2V$ is very small, and in some species the mineral is sensibly uniaxial.

(c) **Zinnwaldite** is closely similar to lepidolite in its essential composition, and like it, occurs in pegmatites and particularly in greisens (see p. 208).

THE DARK MICAS

These stand in strong contrast to the group considered above, not only in appearance and optical orientation, but also in mode of occurrence and distribution in rocks.

(a) **Biotite**.—This is the common black mica that extends through the whole range of rocks from acid to ultrabasic. Biotite (or glimmerite) consists almost solely of this mineral, while at the other end of the scale the black glistening plates of biotite immediately catch the eye in hand-specimens of granites, while some Indian pegmatites yield biotite crystals a yard across. Among many other biotite-rich rocks certain types of lamprophyres are outstanding. In these the crystals are often euhedral and zoning may be well developed in the biotites (Fig. 130). Biotite shows better than any other mineral the effects of internal bombardment by alpha particles emanating from radioactive elements in zircon inclusions. This bombardment causes concentric zones of discoloration round the inclusions, and is seen in thin sections as pleochroic haloes. Biotite alters rather readily into a light green chlorite, first along the cleavages, but ultimately the whole crystal may be replaced.

The optical orientation of biotite is as shown in Fig. 29. The angle $2V$ is very small, so that on rotation of the stage the isogyres must be closely watched to see that they do actually separate. Further, very strong illumination must be employed, as the absorp-

tion is particularly strong in basal sections, so much so that even in thin sections no light is allowed to pass in some cases. Vertical sections are almost violently pleochroic, the vibration parallel to X yielding a light (straw-) yellow absorption tint, while the Y and Z vibrations are usually indistinguishable, giving equally dark brown,

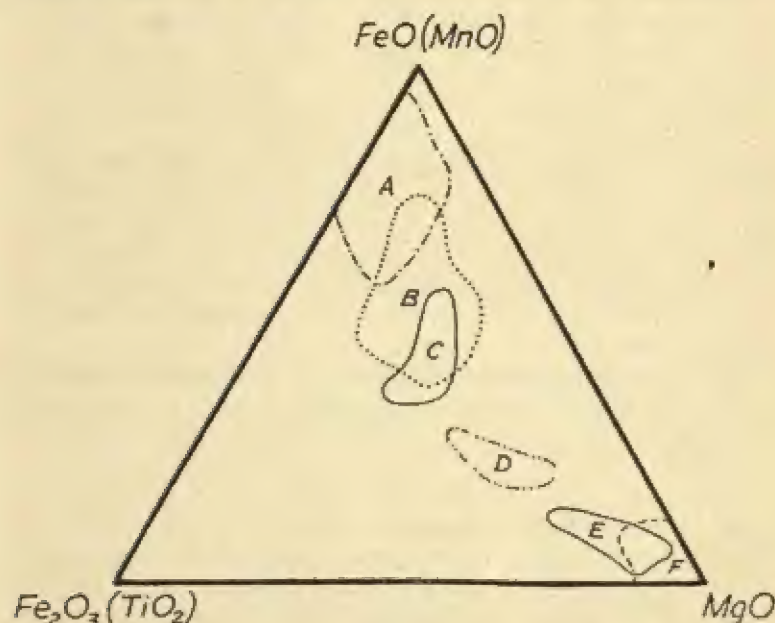


FIG. 30

Diagram showing the variation in composition of micas of the biotite-phlogopite series in rocks of different kinds.

- A—Dark micas from granite-pegmatites.
- B—Dark micas from granites, granodiorites, etc.
- C—Dark micas from tonalites and diorites.
- D—Dark micas from gabbros.
- E—Dark micas from ultrabasic rocks.
- F—Phlogopites from metamorphosed magnesian limestones.

Data by E. Wm. Heinrich.¹

sometimes nearly black. It follows that a basal section is non-pleochroic: there is no perceptible change on rotating such a section over the polarizer.

(b) **Phlogopite**, often called the bronze mica on account of its colour, is much less widespread in igneous rocks than biotite, and is in fact more characteristic of certain types of metamorphosed

¹ "Studies in the Mica Group," *Am. Journ. Sci.*, cexliv (1946), p. 836.

magnesian limestones, which in the hand specimen may be studded with small, perfect, bronze-coloured phlogopites set in a matrix of crystalline calcite. In igneous rocks true phlogopite is relatively rare, but occurs in the leucitic lavas of Wyoming, Western Australia and parts of East Africa. These are thoroughly basic rocks, and once again it appears that within the biotite-phlogopite group the types with the highest ratio of Mg to Fe characterize the most basic rocks, while the iron rich varieties are commonest in the acid rocks (Fig. 30).

In thin section phlogopite is typically much less strongly coloured than biotite: even in a basal section the colour may be no deeper than a light orange brown. Thus a basal section will exhibit pleochroism, for there is an appreciable difference in the absorption of the Y and Z vibrations, the latter being the more strongly coloured. The vibration parallel to X, *i.e.* perpendicular to the cleavages, is the least absorbed, and may be nearly or quite colourless. In convergent light phlogopite yields a typical biaxial interference figure, with small 2V.

(c) **Lepidomelane** is the name given to biotites notably rich in iron, and characterized by a deep red-brown colour in thin section.

THE SILICA GROUP

Several distinct mineral species consist of pure silica, SiO_2 ; some of these occur as good crystals, others as cryptocrystalline aggregates, while amorphous silica also occurs naturally.

Each of the three mineral species quartz, tridymite and cristobalite occurs in both high- and low-temperature modifications, distinguished as beta (or high-) and alpha (or low-) quartz, etc. The complete range of six minerals forms a series stable under varying physical conditions. The significant temperatures, determined experimentally, are 575°C , the inversion temperature between α - and β -quartz; 870° , above which quartz gives place to tridymite; $1,470^\circ$, at which cristobalite replaces tridymite; and $1,710^\circ$, the melting point of high-cristobalite. These several forms of SiO_2 may persist, however, far below the temperatures at which theoretically inversion should take place, as most of the inversions are very sluggish.

In all these silica minerals SiO_4 -tetrahedra are linked to one another by all their corners. The actual arrangement of the atoms is complicated and impossible to illustrate simply. The important fact is that the tetrahedra form spirals in both forms of quartz, the arrangement being somewhat more symmetrical in the high than in the low-temperature form: thus while α -quartz crystallizes in the

holo-axial (trapezohedral) class of the Trigonal system, β -quartz belongs to the corresponding class of the Hexagonal system.

Alpha quartz is the quartz of mineral veins and vugs: it does not occur, except as a product of inversion, in normal igneous rocks. Its crystal characters are indicated in Fig. 31. Usually there is a distinct difference in the degree of development of the two rhombohedra

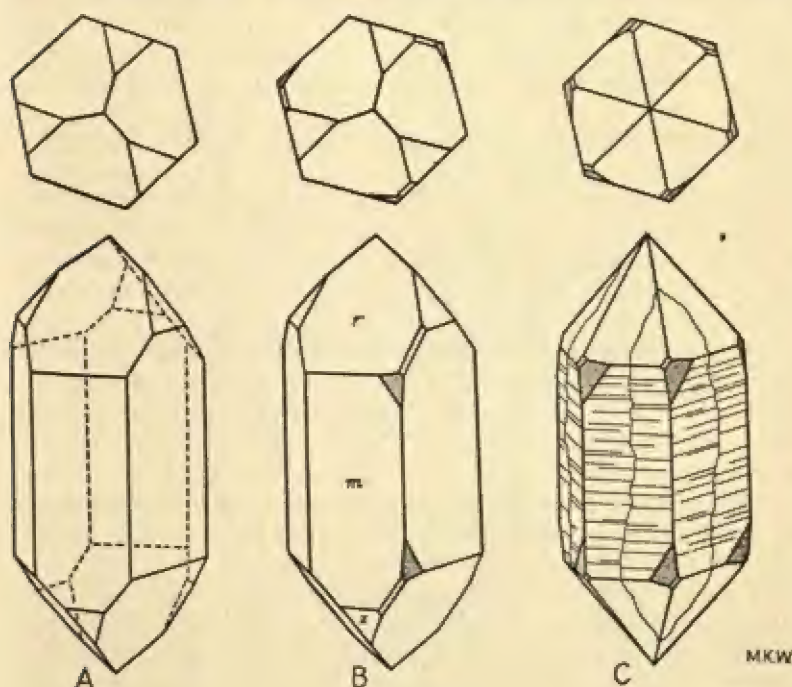


FIG. 31

Quartz crystals: (A) Simple combination of positive (r) and negative (s) rhombohedra and vertical prism (m); (B) A right-handed crystal showing the same forms, with trapezohedron ($51\bar{6}1$) and trigonal bipyramid; (C) A double left-handed Dauphiné twin. *Trigonal trapezohedron faces stippled.* (After Parrish and Gordon.)

(positive and negative); and special forms, particularly trigonal trapezohedra and trigonal bipyramids show these crystals to be fundamentally different from those of β -quartz.¹ The latter show a combination of hexagonal prism and hexagonal bipyramid: these

¹ Quartzes from the iron mines of north-western England show the simple crystallographic character normally associated with the β -phase, but they are definitely low-quartz. Apparently the presence of the haematite affects the crystal habit of the silica.

are forms characteristic of the holosymmetric class of the Hexagonal system; but actually it is known from the internal structure of the mineral that it belongs to the trapezohedral class of that system.

Twinning is apparently ubiquitous in α -quartz, according to a variety of laws; but it can only be demonstrated by means of external characters *in some cases*—notably by the occurrence of the form $(51\bar{6}1)$ on contiguous faces, instead of on alternate ones (Fig. 31, C). Otherwise the twinning can be demonstrated by special optical tests¹—not by the examination of sections of normal thickness.²

The most distinctive optical character of quartz is its extraordinary power of causing rotation of the plane of polarization, in the manner of a clockwise spiral in some cases, but anti-clockwise in others. This is evidently due to the essentially spiral arrangement of the atoms, which finds expression in the development of two types of crystal, termed left- and right-handed respectively, according to the position of the trapezohedral faces (Fig. 31, B). Quartzes of opposite hand are mirror-images of one another, and are said to be enantiomorphous. The degree of rotation of the plane of polarization is not sufficient to produce an appreciable effect in a thin section; but a thick section examined in convergent light yields a distinctive interference figure, in which the usual concentric coloured rings are seen, but the black cross has disappeared, and its place near the centre of the figure is taken by an interference colour depending on the thickness.

Another direct consequence of the internal structure of vein-quartz is the difference in polarity at the opposite ends of the three lateral axes. As a result, quartz exhibits piezoelectric properties to a unique degree, and is in great demand for the manufacture of quartz-oscillator constant frequency plates for use in radio equipment.

Despite the many interesting and indeed unique crystallographic and electrical properties of quartz, the optical characters exhibited in thin sections are of a somewhat negative character. Its refractive indices are low (1.553 and 1.544), with consequent absence of surface relief; it has no cleavage, and the birefringence (0.009) is weak. It even lacks distinctive alteration products, for it is completely stable. These details apply to both the α - and β -phases, and there are, in fact, no definite tests available for differentiating between

¹ By immersing a thick basal section of quartz in oil of the same refractive index and viewing it along the direction of the optic axis between crossed plates of polaroid.

² For much interesting information on the twinning, etc., of quartz, see "Symposium on Quartz Oscillator Plates," *Amer. Min.*, xxx (1945), p. 205.

the two in thin section. Both phases of quartz are liable to contain inclusions of several different kinds, sometimes in such quantity as to render the crystals opaque or at least "milky." Frequently the inclusions are minute gas- or fluid-filled cavities (Fig. 32), often lying in curved planes that evidently represent resealed fractures. The fluid cavities may contain a gas bubble, mobile in some cases, or even a minute apparently cubic crystal. In some instances the cavity is bounded by plane surfaces giving a *negative crystal* of minute size but perfect form. In other cases acicular needles of rutile are embedded in the quartz. In the curious Indian granitic rocks

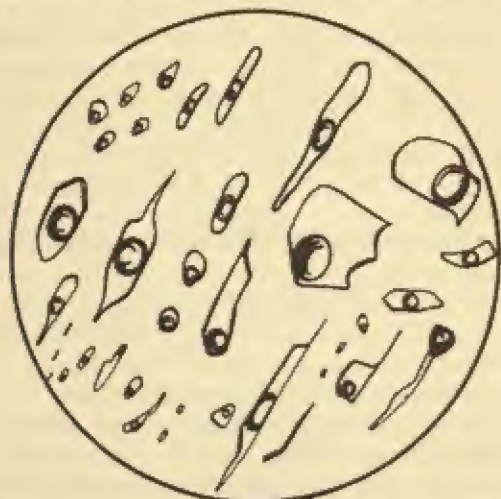


FIG. 32

Fluid cavities containing gas bubbles in α -quartz—highly magnified.

termed charnockites, they are exceedingly minute and occur literally in myriads. They produce an optical blue colour in the crystals in which they occur. In smaller numbers they can often be seen in some Scottish granites, for example, but they are so minute that it is only by analogy with the much stouter prisms that sometimes occur, that they can be identified as rutile.

High-temperature quartz is widespread in igneous rocks, and is diagnostic of those in the granitic clan: it forms shapeless grains in ordinary granites and microgranites, but occurs in euhedral bipyramids in the rapidly cooled fine-grained rhyolites, pitchstones and "quartz-porphyrries." At a late stage in their cooling history such bipyramids may show the effects, sometimes intense, of magmatic corrosion (Fig. 92). The study of twinning in β -quartz has been somewhat neglected as the phenomenon produces no visible

effects in thin rock-sections: but it has been shown to be quite normal. Collections of milky crystals of β -quartz from Cornish quartz-porphyrries were found to contain many twins, the twin-plane being either a face of a rhombohedron or a trapezohedron.¹ The angle between the c-axes of the two crystals involved varies in different types between 43° and 84° . The so-called Japanese twins are of these types.

Tridymite is the Orthorhombic form of SiO_2 stable above 870°C . At its best it forms tabular plates of almost perfect hexagonal shape; but more commonly occurs as twinned groups of minute crystals, in fine-grained rhyolitic rocks, the best known British examples occurring in the Tardree rhyolite, where the tridymite lines small cavities. The high-temperature form of tridymite exhibits higher symmetry, and appears to be Hexagonal holosymmetrical. Optically tridymite differs from quartz in its lower refractive indices (1.473 and 1.469) and weaker birefringence (0.004); but its most distinctive characters are the narrow, lath-like crystals and the twinning.

Cristobalite, stable above $1,470^\circ \text{C}$, has been long known from its development in silica bricks used for lining furnaces. Since the advent of X-ray analysis, however, it has proved to be much commoner than was formerly believed in several classes of igneous rocks. As might be expected, these are usually "acid." Cristobalite is an important constituent of spherulites in rhyolitic lavas, for example from the Yellowstone Park.² The mineral is Cubic, and in certain Hungarian rhyolites cristobalite forms minute crystals, 30 to 60 microns in diameter, in parallel growths, spinel twins and radial aggregates lying between the spherulites, which, it is suggested, are themselves high-cristobalite. Somewhat unexpectedly, it has been discovered in the form of half-millimetre cubes and rare cube-octahedrons on the fracture surfaces of olivine-basalt from Plumas Co., California; while it has been recorded from the groundmass of certain Japanese basaltic lavas. Finally, it may be noted, that the **silica-glass** of problematical origin occurring on the surface of the Libyan Desert, contains small spherulites of cristobalite up to a millimetre in diameter.³

Cryptocrystalline Silica.—There are many varieties of very finely crystalline silica ranging from radially-disposed acicular crystals (fibro-chalcedony) to cryptogranular aggregates difficult to resolve even with high magnification. They are variously coloured, and although the general name chalcedony covers all varieties, such

¹ Drugman, J., "On β -quartz twins from some Cornish localities," *Min. Mag.* xxi (1927), p. 336.

² Howard, A. D., *Amer. Min.*, xxiv (1939), p. 485.

³ Spencer, L. J., "Tektites and silica-glass," *Min. Mag.* xxv (1939), p. 436.

names as carnelian, bloodstone, prase and chrysoprase are used for richly-coloured specimens which are used for ornamental purposes. These forms of chalcedony do not occur as primary minerals, but as secondary products they are widespread. The best-known mode of occurrence is as vesicle- and geode-infillings. The relationship of chalcedony—chalcedonite is a better mineral name—to quartz is uncertain. In many instances the two minerals have obviously had a common origin, and both can form from colloidal silica, for while the marginal parts of geode-infillings may consist of colour-banded chalcedonite, associated in the well-known agates with opaline silica, the inner parts consist of quartz mosaic, sometimes passing inwards into well-terminated quartz crystals, in some cases of the violet-tinted amethystine variety. At the same time it is stated that chalcedonite differs from quartz in the details of its optical properties. Even the sign of elongation of the fibrous forms varies, so that possibly more than one mineral species is involved. Nevertheless, X-ray studies have revealed no essential structural difference between quartz and "chalcedony." Nevertheless, X-ray studies have revealed no essential structural difference between quartz and "chalcedony."

Amorphous silica.—This substance occurs in two natural forms: as opal, familiar in its precious form, of course, though common opal, colourless in thin section, and having the same mode of occurrence and origin as chalcedonite, occurs as a secondary product in a variety of rocks. It is identified by its low index, which is somewhat variable according to the amount of water which it contains, but averages 1.445: thus it exhibits a distinct negative surface relief. Normally it is isotropic, but sometimes optical anomalies, particularly very weak birefringence, may be observed. Secondly, silica-glass in a number of forms, though a rarity, has been collected from widely-scattered localities. Some forms such as moldavite are apparently of meteoric origin, but other types probably arise as a consequence of the impact of a meteorite, the heat generated being sufficient to cause widespread fusion of superficial deposits, particularly desert sands.

THE FELDSPAR GROUP

The feldspars are quantitatively the most important of the rock-forming silicates. They are all aluminosilicates of potassium, sodium, calcium or rarely barium, and crystallize in the triclinic and monoclinic systems. Although obviously there are differences in the details of the atomic structure of the triclinic as compared with the monoclinic members of the group, fundamentally they are much alike. The three-dimensional framework of linked SiO_4 -tetrahedra may be resolved into "chains" of a special type, which are joined to

one another by sharing oxygens¹ (Figs. 33, 34). The chains are aligned parallel to the a -axis (clino-axis) of the crystal, and two of these, in mirror-image relationship across a plane parallel to (010), occupy the unit cell.

Each single link of the chain consists of four SiO_4 -tetrahedra; but as all the oxygens are shared, it may be said to contain Si_4O_8 . Further, in each of these units, one Si is displaced by a proxy-Al, so the unit formula becomes $(\text{AlSi}_3)\text{O}_8$. This leaves a surplus negative

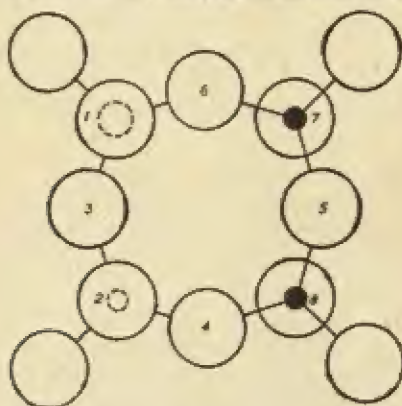


FIG. 33

A single link in the feldspar "chain": with eight oxygen atoms lying in the plane of the paper, two (Nos. 1 and 2) above, and two (Nos. 7 and 8) below the plane. Three silicons occur in the link (one hidden by oxygen 2), and one proxy-aluminium (behind oxygen 1).

charge, which in one important group of feldspars is balanced out by the addition of a K-atom, giving the formula of orthoclase:— KAlSi_3O_8 . In another important member Na-atoms occur in the place of K, giving albite, $\text{NaAlSi}_3\text{O}_8$. A third member is anorthite, which contains Ca in place of K and Na; but as Ca is divalent, an adjustment has to be made. A second proxy-Al^{'''} is introduced in place of another Si^{'''}, so the complete formula becomes $\text{CaAl}_2\text{Si}_2\text{O}_8$. Finally, in rare cases Ba^{''} fills the rôle of Ca^{''}, giving celsian, $\text{BaAl}_2\text{Si}_2\text{O}_8$.

Now as the K and Ba atoms are of approximately the same radius, they are capable of mutual replacement, and feldspars such as hyalophane occur, having a composition somewhere between orthoclase and celsian. Similarly, Ca can replace Na to almost any

¹ Although we use the word "chain" for ease of interpretation, this is not comparable with the chains and bands of pyroxenes and amphiboles respectively, which were self-contained and joined to one another through the medium of the cations. In the feldspar structure, however, the "chains" are linked together left and right, in front and behind, by sharing oxygens.

extent, giving a continuous variation in composition between the two extremes represented by albite and anorthite. These "soda-lime feldspars" are known as the plagioclase series.

By contrast, Na cannot replace K in a manner which will retain the original structure, and therefore homogeneous Na-K feldspar comparable with plagioclase does not occur, except at high temperatures (see below).

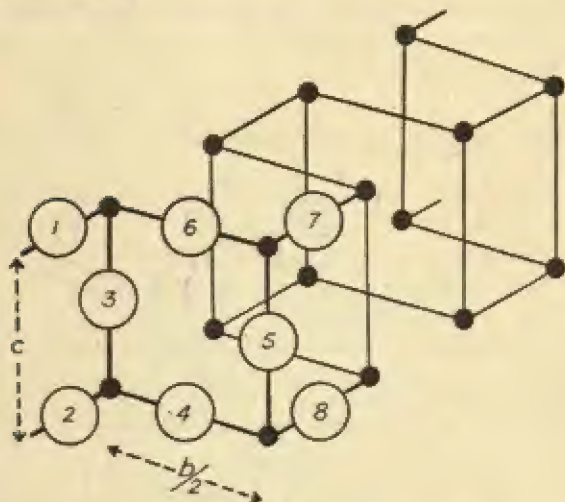


FIG. 34

A formal diagram of the "chain" structure of feldspar. Silicon and proxy-aluminum shown in black. To avoid overcrowding the diagram, only the "shared" oxygens in the single link, represented in Fig. 33, are included. The chain is half the width of the unit cell, and runs from back to front, parallel to the *a*-axis.

The formulae so far considered are those of pure feldspars, of ideal composition, and in the account which follows are represented by Or, Ab, An and Ce. Natural feldspars are actually ternary systems, consisting of various proportions of Or, Ab and An, and are therefore best represented by points on a triangle which has these three components at its apices. The three components are measured in the directions of the arrows in Fig. 35. The dots on the triangle represent the compositions of several hundred feldspars. It will be seen that there is a maximum concentration near the Or apex, which indicates the range of composition of the natural K-feldspars. The average K-feldspar can be seen to have the composition approximately of $\text{Or}_{76}\text{Ab}_{20}\text{An}_4$. The marked concentration of points just above the base-line indicates the range of composition of the plagioclases. It will be noted that on average the plagioclases, although funda-

mentally Na-Ca feldspars, contain about 5 per cent (or more) of Or. The absence of points in field 4 (Fig. 35) reflects the fact that Or and An will not mix: in other words Ca and K, on account of dissimilarity in atomic radius, are not mutually replaceable in the atomic structure.

General Characters of the Feldspars.

In the monoclinic feldspars the simplest combination of faces consists of the basal pinacoid (001), side-pinacoid (010) and prism

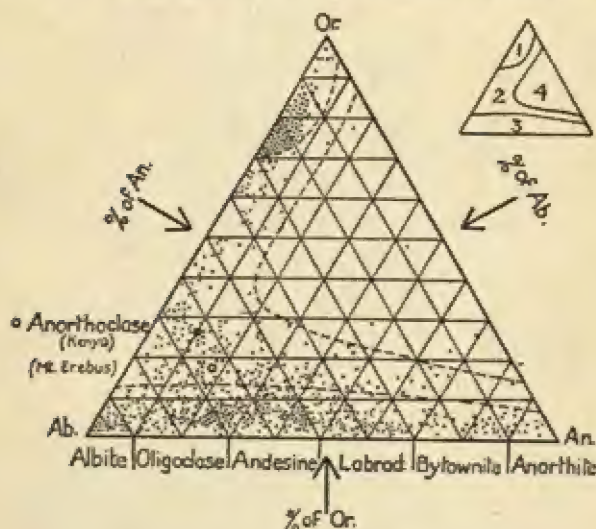


FIG. 35

Diagram illustrating composition of natural feldspars in terms of the Orthoclase, Albite and Anorthite molecules. (After H. L. Alling and A. N. Winchell.) Note maximum concentration in fields 1 (Orthoclase and Microcline) and 3 (Plagioclases). Perthites, unstable at low temperatures, fall in field 2.

(110). A slightly more complicated crystal is illustrated in Fig. 36.

In the triclinic feldspars although crystal faces are developed in analogous positions, and although they superficially resemble the monoclinic crystals, the lower symmetry causes the monoclinic prism to be represented by two complementary hemi-prisms, *m* and *M*. Similarly the hemibipyramid of the monoclinic feldspars becomes the quarter-bipyramid of the triclinic types. The better cleavage in all feldspars is parallel to (001); but that parallel to (010) is little inferior. Naturally these two cleavages are at right angles in monoclinic feldspars, but intersect at angles between approximately 93° and 94° in the plagioclases.

THE ALKALI FELDSPARS

In this category we include the K-feldspars, the Na-feldspars and the various combinations of the two which are distinguished as perthites, etc. (see below).

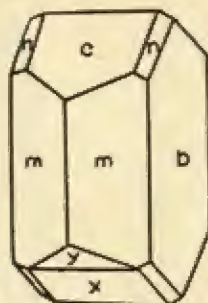


FIG. 36

Crystal of orthoclase (Carlsbad habit).

c Basal pinacoid (001).

b Clinopinacoid (010).

m Prism (110).

x and *y* Hemi-orthodomes (20 $\bar{1}$) and (10 $\bar{1}$).

o Hemi-bipyramid (111).

n A clinodome (or clinoprism) (011).

(1) *The Potassic Feldspars.*

Although identical in composition, several distinct feldspars, one triclinic, the others monoclinic, fall in this group. Orthoclase, sanidine and adularia are monoclinic, while microcline is (just) triclinic.

(a) **Orthoclase.**—This is the form of KAlSi_3O_8 which is a characteristic mineral in granites. It occurs in a variety of crystal habits: the so-called Carlsbad habit, flattened parallel to (010); the Baveno habit, elongated parallel to the clino-axis; the Adularia habit, in which the side-pinacoid is virtually suppressed (Fig. 37). As a rule these crystals are terminated by the basal pinacoid and a hemi-orthodome (*x*). These form a roof-like termination. They are easily identified, however, by noting their different relationship to the basal cleavage (Fig. 37, right).

Orthoclase crystals are frequently twinned in distinctive fashion (Fig. 38), on one or other of the following laws:—

Carlsbad, usually interpenetrant and resulting from rotation about the *c*-axis;

Baveno, in which twin-plane and composition-plane are parallel to a clinodome (011);

Manebach, in which twin-plane and composition-plane are parallel to (001).

Of these the first is much the commonest; Manebach and Baveno twinning are uncommon in orthoclase, but less rare in sanidine.

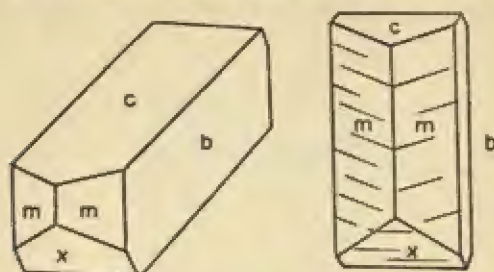


FIG. 37

Crystal habits of orthoclase.
Left, Baveno habit. Right, Adularia.

The refractive indices of orthoclase are low: γ , 1.525; α , 1.519, both well below Canada balsam. Birefringence also is weak (0.007)—a little lower than the quartz by which it is normally accompanied in igneous rocks. The optic axial plane is perpendicular to the plane of crystallographic symmetry (010), and is inclined at 5° to 8° to (001). Therefore the extinction is oblique to this extent in (010) sections. The angle $2V$ is large, but on heating it progressively diminishes, and becomes 0° at a certain temperature, above which the axes open out in the symmetry plane (010) (see Fig. 39).

(b) **Sanidine**.—On heating orthoclase inverts into sanidine at the inversion temperature, 900°C . As might be expected, therefore, sanidine is the form of K-feldspar occurring in quickly-cooled lavas and some dyke-rocks, including rhyolites, trachytes, pitchstones, etc. It may persist indefinitely in these rocks, in the metastable state; but with the slow cooling characteristic of deep-seated rocks sanidine inverts into orthoclase. The only significant difference between the two minerals in thin section is the difference in orientation of the optic axial plane, noted above, and the small, to very small, $2V$ in sanidine. When unweathered sanidine is clear and glassy.

(c) **Adularia**.—This is the name of a crystal habit rather than a distinct mineral species as noted above, but is commonly applied to a variety of orthoclase of prismatic habit occurring in mineral veins and as incrustations in vugs. It may be opaque like any other type of orthoclase, or glassy like sanidine.

(d) **Microcline**.—This is the triclinic form of K-feldspar, but the departure from monoclinic symmetry is so slight (the angle between (001) and (010) being $89^\circ 50'$) that there may be no appreciable difference in the hand-specimen between microcline and orthoclase.

Under the microscope, however, microcline is very distinctive by reason of a complex system of spindle-shaped twin lamellae in two sets nearly at right angles in (001) sections (Fig. 40). The twinning

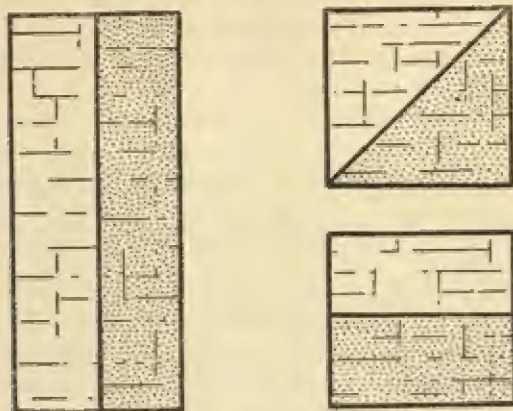


FIG. 38

Vertical sections through twins of orthoclase.
Left, Carlsbad; Right top, Baveno; Right bottom, Manebach.

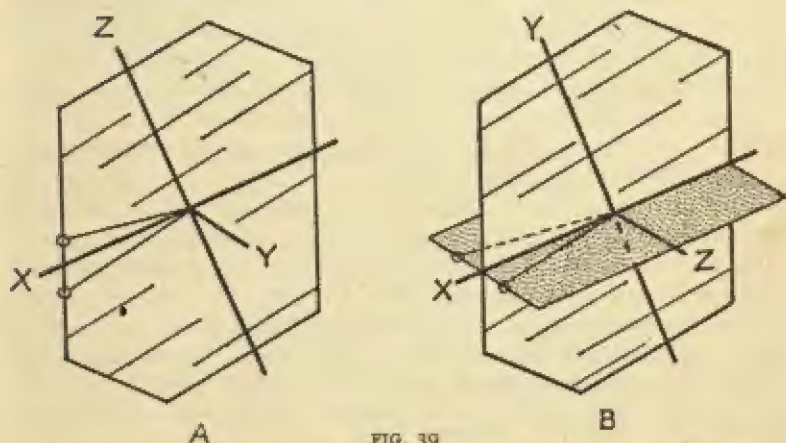


FIG. 39

Diagram showing optical orientation of sanidine (A), and orthoclase (B).
 Optic axial plane stippled in B.

may affect only part of a crystal, or it may be absent altogether, but when found, it is completely diagnostic. Refractive indices (γ 1.529, α 1.522) and birefringence (0.007) are very similar to those of orthoclase, but on account of the triclinic symmetry, the extinction

in a (001) section is oblique (extinction angle 15° to the (010) cleavage traces).

Although most types of microcline are coloured red or brown, specimens from pegmatites from Colorado and elsewhere are bright green in the variety known as **amazonstone**. This contains the rare elements caesium and rubidium, and the depth of colour is said to be proportional to the amount of the latter.

Microcline is practically restricted to the highly potassic granites and pegmatites. It is rarely pure K-feldspar, but contains Na-feldspar in solid solution or intergrown as perthite or micropertthite, as described below.

(2) *The Sodic Feldspars.*

Three named minerals occur in this group, albite, barbierite and clevelandite. Of these the first-named is of outstanding importance.

(a) **Albite**.—The status of albite among the feldspars is somewhat anomalous: it is rightly regarded as one end-member of the plagioclase series; but obviously it is an alkali-feldspar, with the same status as orthoclase. It stands in striking contrast to typical soda-lime plagioclase as regards its rôle in rock-building (see pp. 92, 233). It is stable under widely varying conditions, including those under which the Ca-rich plagioclases tend to decompose, so that it is often seen to have replaced Ca-Na plagioclase in such rocks as gabbros and dolerites, particularly when the latter have been subjected to slight dynamothermal metamorphism. As might be inferred from this, albite is characteristic of some types of schists and gneisses. It is specially abundant in the sodic syenites, one type of which, termed albitite, is nearly monomineralic.

In its crystallographic and other physical characters, albite is like the other members of the plagioclase series, as described below.

(b) **Clevelandite**.—This mineral bears the same relationship to albite as adularia bears to orthoclase: it occurs chiefly in pegmatites and sometimes in mineral veins, in aggregates of tablet-like crystals flattened parallel to (010). Again it is the name of a crystal habit rather than a distinct mineral species.

(3) *The Sodi-Potassic Feldspars.*¹

Both orthoclase and microcline are frequently intergrown with albite, which occurs in the form of orientated plates or threads embedded in the host feldspar (Figs. 40, 41 and 42). The intercalations do not follow the planes of weakness (cleavage directions) in the host feldspar, but must be related to structural directions

¹ Spencer, E. Edmonson, "The Potash-soda Feldspars," *Min. Mag.*, xxiv (1937); and *Min. Mag.*, xxv (1938), p. 87.

dependent upon the internal structure (Fig. 42). The following types of perthite have been described and figured: vein-perthite (probably the commonest), film-perthite, and braid-perthite in which the albite sheets are arranged parallel to the prism faces (110) and ($\bar{1}\bar{1}0$), and thus give a braided appearance in a basal section. Less regular intercalations are known as patch- and string-perthite which, on account of the lack of orientation, may have originated differently. The intergrowths may be megascopic, microscopic, or on so fine a

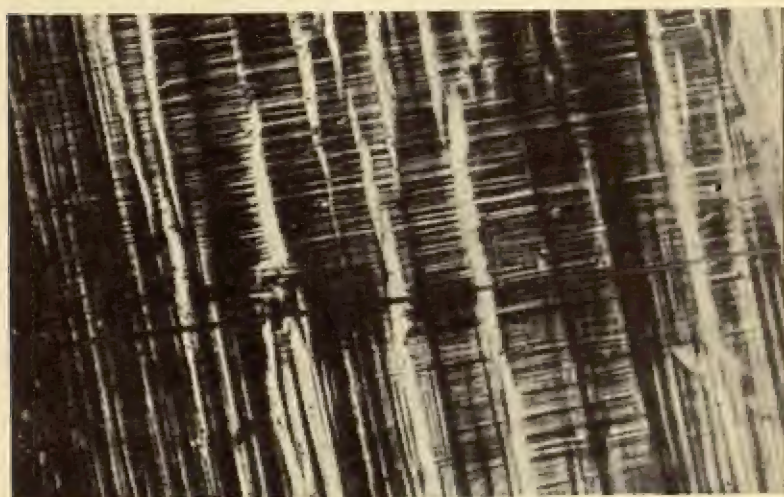


FIG. 40

Thin section of microcline-albite perthite, Hylba, Ontario. The original is a typical green amazonstone, with megascopic veins of white albite.

Crossed polarizers. Photomicro. by E. O. Rowland. Section parallel to (001).

scale as to be beyond the resolving power of the microscope. The three terms perthite, microperthite and cryptoperthite are applied to these, respectively; and in the case of microcline being the host feldspar, the mineral name is added as a qualifier: thus, "microcline-microperthite" indicates an intergrowth of microcline and albite on a microscopic scale.

The terms soda-orthoclase and soda-microcline are sometimes given to cryptoperthites of the appropriate composition: they are chemically alike.

The phenomenon of perthitic intergrowth results largely from exsolution. It is believed that at high temperatures the atoms of sodium and potassium are so arranged as to give a homogeneous sodi-potassic feldspar. At some lower temperature (the exsolution

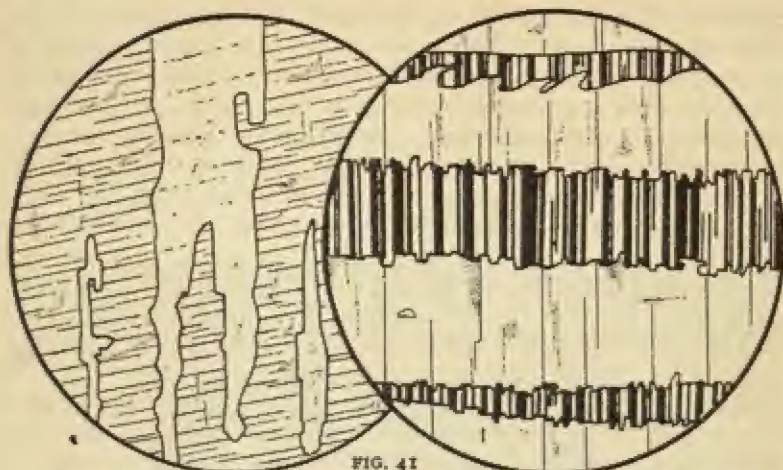


FIG. 41

Formalized sections through vein perthite (albite veins in microcline). *Left*, a (010) section in plane polarized light; (001) cleavage shown. *Right*, a (001) section showing the nature of the margins of the albite veins against the host-microcline, and the (010) cleavage-traces.

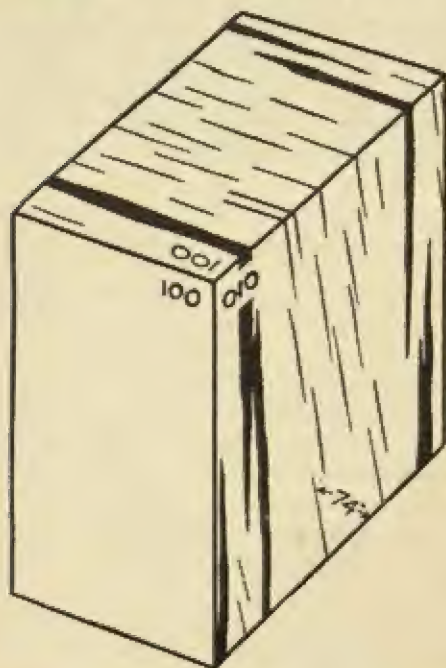


FIG. 42

Block-diagram showing relation of film- to vein-perthite in K-Na feldspar.

temperature), the atoms are so rearranged as to segregate the sodiums into regularly orientated sheets or films, the disposition of which is determined by the atomic structure. This involves atomic diffusion in the solid feldspar, while its temperature is still high. X-ray analysis proves the coexistence of two independent lattice-structures in perthites, one due to orthoclase, and the other to albite. If a perthite is heated to near 850°C , the perthitic structure disappears, but reappears on cooling—the change is reversible; but when heated to a higher temperature for a longer period of time, a stable homogeneous feldspar is obtained, which has the optical orientation of sanidine. Even when the intergrowth is on a submicroscopic scale, it may produce distinctive optical effects. To this cause are due the striking blue "schiller" of anorthoclase, and the beautiful sheen of moonstone,¹ which is merely a microperthite in which the lamellae are exceptionally thin in the much prized blue examples, but thicker in the commoner white types.

THE PLAGIOCLASE SERIES

It has long been known that the members of this series show a gradational variation in composition between the two end-members, albite and anorthite. For descriptive purposes it is necessary to use a number of names to fix certain ranges of composition. Using the convention already described, we may note that, ignoring the small amount of Or present, the composition of any specific plagioclase may conveniently be expressed by a simple symbol, indicating the molecular percentages of Ab and An which it contains. Thus the full range extends from $\text{Ab}_{100}\text{An}_0$ to $\text{Ab}_0\text{An}_{100}$. As the variation is continuous the several kinds of plagioclase are defined arbitrarily by erecting divisions at Ab_{100} , 30, 50, 70 and 90. These are the widely agreed limits between albite, oligoclase, andesine, labradorite, bytownite and anorthite respectively. The percentage composition of three selected plagioclases is tabulated below:—

	SiO_2	Al_2O_3	Na_2O	CaO
Albite (Ab)	68.7	19.5	11.8	0.0
Labradorite ($\text{Ab}_{30}\text{An}_{70}$)	55.6	28.3	5.7	10.4
Anorthite (An)	43.2	36.7	0.0	20.1

Since the ratio of the molecular weight of Ab to An is as 1 : 1.061, it is approximately accurate to calculate the relative weights of the two components (Ab and An) in the proportion of the number of molecules. Thus $\text{Ab}_{60}\text{An}_{40}$ contains Ab three-fifths and An two-fifths by weight.

¹ Spencer, E. Edmonson, ". . . moonstone from Ceylon . . .," *Min. Mag.*, xxii (1930), p. 291.

Detailed examination of the optical characters of the plagioclases using Universal Stage technique, has shown that high- and low-temperature forms exist in rocks crystallizing under different conditions. The "high" forms occur in lavas and experimental melts; while the "low" forms are characteristic of plutonites and pegmatites.¹

Crystallographically the plagioclases differ from orthoclase by having the basal pinacoid (and the cleavage parallel to it) inclined to the side-pinacoid (010) at an angle of 86° to 87° instead of 90° ; otherwise they are closely similar in appearance and cleavage. Plagioclase may be twinned in any of the ways in which orthoclase twins, but in addition exhibits two special types which are distinctive. Plagioclase of any composition may be twinned once or repeatedly on the Albite Law, in which twin plane and composition plane are (010). Secondly, in twinning according to the Pericline Law, twin plane and composition plane vary systematically in the manner shown in Fig. 43. The pericline, like the albite twinning, is commonly repeated, and in both cases the twin-bands are thin, and give a characteristic lamination between crossed polarizers (Fig. 44). Both types may be associated with simple twinning on the Carlsbad law (Fig. 44). Sometimes these features can be seen with the naked eye, and more readily with a lens, but they make the plagioclases unmistakably distinctive in thin sections.

Statistical studies² of the frequency of occurrence of the several types of twins shows that normally twinning is more complex in igneous than in metamorphic rocks; in those of high grade, as compared with low grade metamorphism; and in plagioclase of calcic, rather than sodic composition. Thus, in low-grade metamorphic rocks untwinned grains are often dominant, and may be exclusive—a condition that is not found in igneous rocks. At a slightly higher grade of metamorphism, simple twinning is characteristic, but is on the albite, NOT the Carlsbad law. In high-grade metamorphic rocks, the complexity may approach that of igneous rocks, but still there are differences. Twinning involving Carlsbad and Manebach combined with lamellar albite and pericline is commonly seen in igneous rocks, especially those of basic type; but such complex twins are typically absent in metamorphic rocks.

Plagioclase crystals often contain numerous inclusions, which may be arranged irregularly or in definite zones parallel to the

¹ Köhler, A., *Min. Petr. Mitt. (Tschermak)*, liii (1941), pp. 24 and 159; also *ibid.*, liv (1942), p. 193; and *Journ. Geol.*, lvii (1949), p. 392.

Tuttle, O. F., and Bowen, N. L., "High-temperature albite and contiguous feldspars," *Journ. Geol.*, lviii (1950), p. 572.

² Turner, F. J., "Twinning of Plagioclase in Metamorphic Rocks," *Amer. Min.*, xxxvi (1951), p. 581, with refs.

periphery of the crystal. The latter is commonly the case with phenocrystic plagioclase in basalts, when the inclusions may be glass, devitrified glass or small patches of the groundmass. In deep-

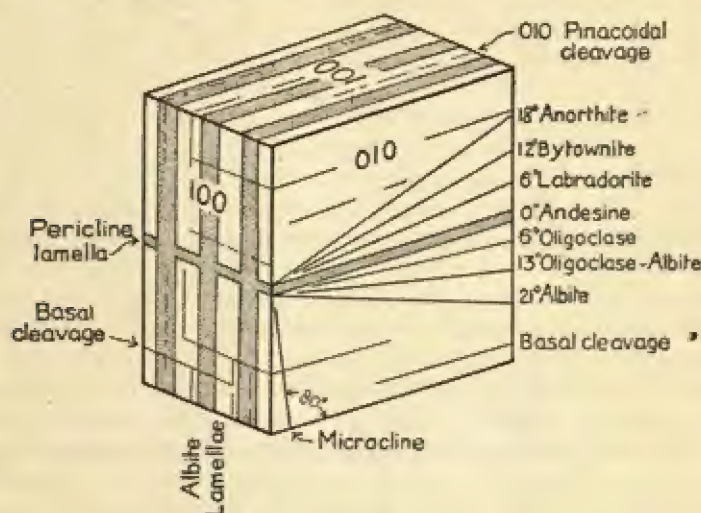


FIG. 43

Block-diagram showing relation between albite and pericline twinning and the cleavages in plagioclase feldspars.

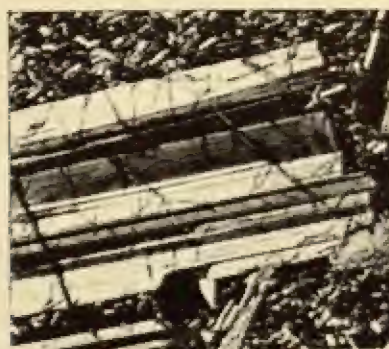


FIG. 44

Twinned crystal of plagioclase feldspar in andesite from Cupar, Fife.
(Photo by Geol. Survey.)

seated rocks, such as certain gabbros, the plagioclase is strongly schillerized and exhibits a striking play of colour in the hand-specimen. In thin slice this is seen to be due to myriads of orientated

rod-like inclusions (Fig. 113). It seems probable that these must have been in solution in the feldspar at high temperature, but were exsolved later.

A definitely zonal structure is more commonly shown by plagioclases than by any other type of mineral.¹ This results from variation in chemical composition during crystal growth, and may be of several different kinds: the commonest involves a gradation from a Ca-rich core to Na-rich outer layers, and is termed *normal zoning*. Less frequently the converse is true: this is *reverse zoning*; while in yet other cases the composition has changed rhythmically, causing *rhythmic* or *oscillatory zoning*. The systematic study of such zoning in plagioclase may throw considerable light on the details of the cooling history of the rock which contains it. Studies of this kind, and indeed normal petrographical work, involves the accurate identification of the plagioclase, or in a zoned crystal, of its individual layers.

Plagioclase is liable to alteration, and occasionally suffers complete replacement by secondary white mica (paragonite), scapolite, zeolites, or minerals of the epidote group, often associated with calcite. The last type of alteration results from slight dynamothermal metamorphism, and results in the separation, as it were, of the Ab from the An. The former is stable; but the latter changes readily under these conditions into zoisite, clinozoisite or epidote, embedded in a "background" of secondary albite.

Status and Distribution of Plagioclase in Rocks.

Plagioclase of one kind or another occurs in representative members of all the main rock groups. Rarely it may make up nearly the whole of the rock: albitite, oligoclase, andesinite and labradorite (under the name anorthosite) have all been described, though only the last is other than very rare.

Apart from these monomineralic types, however, plagioclase is an important—often a dominant—component in many intermediate and basic rock-types. In general, in passing from more acid to more basic types, the plagioclase becomes progressively richer in An: thus in syenitic rocks oligoclase is commonly found; in dioritic (including andesitic) types, it is andesine typically; while in gabbroic (including noritic and basaltic) rocks, labradorite or bytownite occur—in greatest amount in the so-called anorthosites, which are coarse-grained rocks composed essentially of basic plagioclase only.

¹ Phemister, J., "Zoning in Plagioclase Feldspar," *Min. Mag.*, xxlii (1934), p. 541; Fries, C., "Resorbed Feldspars in Basalt," *Amer. Min.*, xxiv (1939), p. 782; Hills, E. S., "Reverse and Oscillatory Zoning in Plagioclase Feldspars," *Geol. Mag.*, 1936, p. 49.

Anorthite is less common: indeed, though it does occur in some gabbroic rocks (such as allivalite, for example), it is more typical of metamorphic rocks. An argillaceous limestone might be expected under thermal metamorphism to give rise to anorthite, among other Ca-rich minerals.

Identification of the Plagioclases in Thin Section.

It is highly important in petrography to be able to determine the composition of plagioclase in a rock, with reasonable accuracy. To distinguish orthoclase or microcline from plagioclase usually presents little difficulty, for they separate from the magma at different temperatures and hence show different crystal habits. It is also almost inevitable that there will be differences in surface relief and in degree of alteration. The twinning is diagnostic in the case of microcline. Orthoclase shows simple twinning only, on any of the three laws already noted; but plagioclase may be untwinned, twinned, simply on these and other laws, or repeatedly on the albite or pericline laws.

As the plagioclases form a continuous series of solid solutions whose properties vary regularly with change of composition, it follows that careful measurement of any one of these properties will furnish a valuable clue to the composition of the specimen under test (Fig. 45).

Measurement of the refractive indices, using the immersion method (p. 30), is one of the most satisfactory techniques, particularly if a set of standard liquids of known indices is available. Most of the methods are based upon optical properties, and several involve the use of apparatus not normally available for students. With the Universal Stage a micro-section of the rock can be swung into almost any desired position for measurement; but with the ordinary petrological microscope the rock-slice has to be searched for suitably cut sections, that is, those lying in a suitable position for measurement. For details reference must be made to one of the standard books on the subject. A good method makes use of sections cut at right angles to the albite twinning.

Such sections show uniform illumination when the twin planes are parallel to the vibration directions of the polarizers, *i.e.* to the cross-wires. The extinction angles for alternate twin bands should be equal to within 2° when measured on opposite sides of the cross-wire. The maximum angle only is diagnostic, and if possible at least six such sections should be measured. Reference to the line on Fig. 45 marked "maximum extinction angles for sections perpendicular to 010" will then give the composition of the plagioclase. In the special case of oligoclase ($\text{Ab}_{50}\text{An}_{50}$) the extinction of both sets of twin lamellae is straight. As the composition changes towards albite, the

extinction angle increases to a maximum of 20° , while andesine ($\text{Ab}_{62}\text{An}_{38}$) also gives this angle. For angles less than 20° , therefore, a confirmatory test must be applied. This is easily done by means of the Becke test (p. 31); the refractive indices of andesine are above, while those of albite are below, Canada balsam.

Sections of plagioclase twinned on both Carlsbad and albite laws

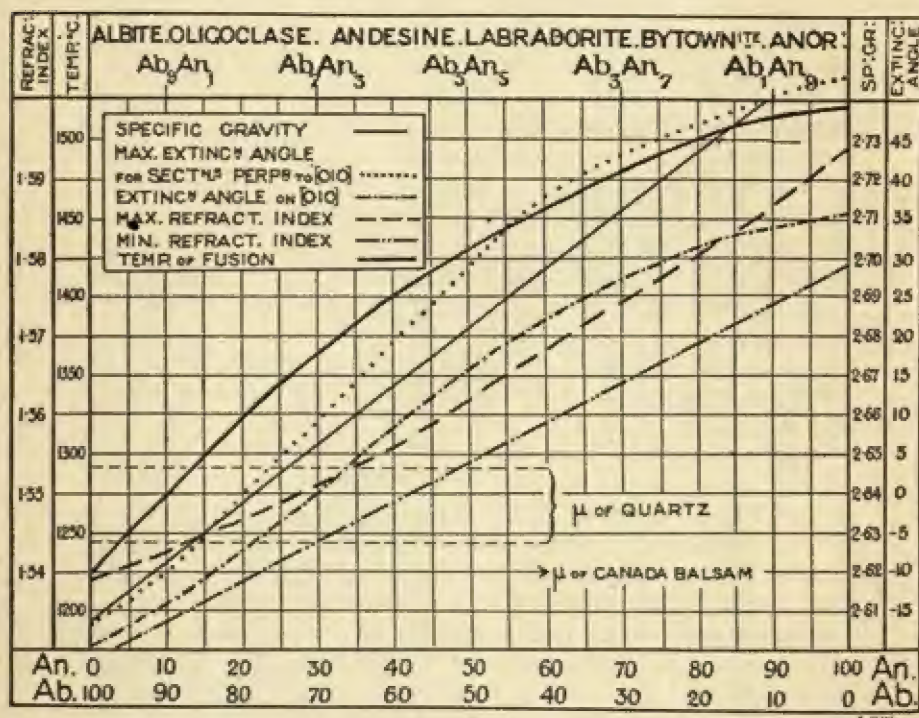


FIG. 45

The physical characters of the plagioclase feldspars.
(Modified after H. L. Alling.)

are of special value in these determinations (Fig. 46). They show uniform illumination when the twin planes are parallel to the cross-wires if the section is perpendicular to the twin planes. In the 45° position they show Carlsbad twinning, but in the intermediate positions all four sets of twin lamellae can be seen. If the four extinction angles are measured, it will be found that two pairs of equal angles have been obtained, and reference to appropriate curves will give the composition required. Fig. 43 suggests yet another method

involving measurement of the angle between basal cleavage and pericline twin-lamellae in (010) sections.

THE BARIUM FELDSPARS

These are definitely the least important members of the group, as they play minor rôles as rock-formers, and are probably unknown as normal constituents of igneous rocks. **Hyalophane**, a K-Ba feldspar occurs in crush zones in an anorthositic rock, and is associated with corundum.¹ There is little doubt that volatiles from a

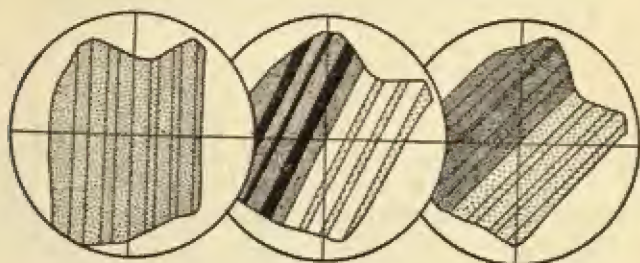


FIG. 46

Sections of Carlsbad-albite complex twin of plagioclase in three positions, between crossed nicols.

nearby pegmatite have effected the exchange, K, Ba for the Ca, Na in the original plagioclase. It is significant that the Ba-zeolite, harmotome, occurs encrusting the joint-faces of the anorthosite at this spot.

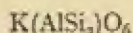
THE FELDSPATHOID MINERALS

In this group are included several minerals which are closely related, as their name implies, to the feldspars. They contain the same elements as the latter, though in different proportions, and are notably poorer in silica.

Leucite, the potassic feldspathoid, resembles orthoclase in composition. The SiO_4 -tetrahedra are linked corner to corner, and if we consider three of these, the unit contains Si_3O_6 . But in each unit of structure one proxy-Al takes the place of one Si; so that the formula of the unit becomes $(\text{AlSi}_2)\text{O}_6$. Balance of the total positive and

¹ Tomlinson, W. H., "Genesis of Corundum in a Dyke at Glen Riddle, Penn.," *Amer. Min.*, xxiv (1939), p. 339.

negative charges is brought about by adding one K atom, giving the completed formula:—



with SiO_2 , 55.0; Al_2O_3 , 23.5; and K_2O , 21.5 per cent.

It is difficult to write about the crystallography of leucite in unequivocal terms. In many mineral collections leucites occur in the form, apparently, of the simple unmodified icositetrahedron; but the optical properties of the mineral prove that it cannot belong to the Cubic System: the form is a *pseudo-icositetrahedron*, resulting from complex twinning of Orthorhombic or possibly Monoclinic crystals which, in the untwinned condition, are unknown in Nature.

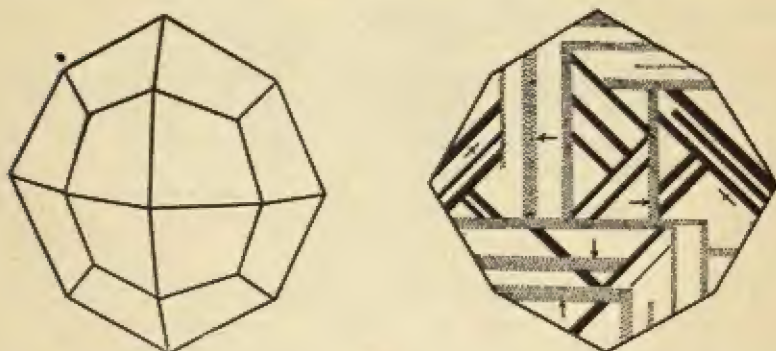


FIG. 47

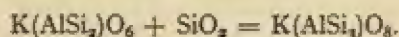
Left, crystal of leucite showing pseudo-icositetrahedral form. *Right*, central section through a leucite crystal between crossed polarizers to show twinning in six directions. Dip arrows and signs for verticality indicate the attitude of the twin lamellae in relation to the section.

In thin slice leucite normally shows characteristic eight-sided sections, when cut through centrally. The refractive index, 1.508, is one of the lowest among common rock-forming minerals. Cleavage is absent; but small inclusions may be arranged in zones or tangentially, especially in the minute leucites occurring in the ground-mass of some lavas. The most significant feature, however, is the twinning (Fig. 47). In a perfect, centrally-cut section twin lamellae in six directions (parallel to the faces of the pseudo-rhombdodecahedron) give a particularly striking appearance, though, on account of the abnormally weak double refraction (0.001), very strong illumination is necessary to make this feature really convincing. The mere fact that the twin planes are parallel to directions which, in a Cubic crystal, would be planes of symmetry, proves that such leucites are not Cubic.

As a fact, the small leucites in the groundmass of a lava do appear to be isotropic between crossed Nicols, and therefore are presumably Cubic. This is notably the case with lavas in which the groundmass crystals are embedded in a base of glass. These facts seem to establish the existence of two forms of leucite: a high-temperature Cubic form, only seen in Nature's quenching experiments; and a low-temperature form occurring as phenocrysts, and exhibiting the twinning described above.

Remarkable pseudomorphs of orthoclase and nepheline after leucite have been described by Hussak, Derby, J. F. Williams, Teall, Shand, and Knight.¹ These *pseudoleucites*, as they are called, whilst maintaining more or less the icositetrahedral form of leucite, have had their leucite-substance replaced by an aggregate of orthoclase and nepheline. The latter mineral is sometimes represented only by a decomposition product. Other minerals such as biotite, augite, hornblende, sphene, etc., are probably inclusions from the original magma in which the leucite crystals were formed.

These interesting pseudomorphs are explainable in the light of Morey and Bowen's work on the melting of orthoclase.² They have proved that in cooling from fusion, a melt having the composition of orthoclase gives rise to crystals of leucite, suspended in a liquid phase more siliceous than the original melt. At 1170° C, a transition point is reached at which the leucite is made over into orthoclase by abstracting silica from the residual liquid. With rapid cooling, as in lavas, the conversion will be inhibited and the unstable form (leucite) will persist. With slow cooling (plutonic conditions), the conversion will be complete and no leucite will remain. Thus leucite, like nepheline, is unstable in the presence of free silica, with which it combines to form the potassic feldspar, orthoclase:



Leucite³ is far rarer than nepheline owing to its virtual suppression in all but the extrusive rocks. It is best developed in certain Intermediate and Basic lavas from the Roman volcanic province in Italy and from the Leucite Hills in Wyoming. The mineral gives its name to two rock-types, leucitophyre (see Fig. 104) and leucitite. The characteristic Vesuvian lavas, which provide most of the specimens in teaching collections, carry prominent grey-white phenocrysts of

¹ Hussak, *Neues. Jahrb.*, ii (1887), p. 255, and i (1890), p. 166; Derby, *Quart. Journ. Geol. Soc.*, xlvii (1891), p. 251; J. F. Williams, *Amer. Journ. Sci.*, i (1895), p. 194; Teall, "Geological Structure North-West Highlands," *Mem. Geol. Surv.*, 1907, p. 443; Shand, *Neues. Jahrb.*, xxii (1906), p. 413; Knight, *Amer. Journ. Sci.*, xxi (1906), p. 786.

² "The Melting of Orthoclase," *Amer. Journ. Sci.* (5), iv (1922), pp. 1-22.

leucite, embedded in a matrix which is essentially basaltic in composition. These are leucite-tephrites and leucite-basanites.

Nepheline corresponds with kaliophilite and kalsilite (KAlSiO_4) in composition, but contains Na instead of K, and is thus represented ideally by the formula NaAlSiO_4 , though actually Na is accompanied by K in natural specimens.

Nepheline crystallizes in the Hexagonal System, in a class showing only one element of symmetry—the vertical hexad axis—but this low degree of symmetry is not apparent from the morphology of the crystals, for they exhibit the simplest possible combination of forms: a hexagonal prism capped by the pedion (0001).

Diagnostic Characters in Thin Section.

Nepheline is one of the more difficult minerals to identify in thin sections. In some rocks in which the mineral occurs as rather squat prisms, many sections are nearly square, while a number are hexagonal. The former are vertical sections; they polarize in grey and extinguish straight. The latter are basal sections, and they remain dark on rotation of the stage (see Figs. 102, 122, and 125).

In many rocks, however, the useful evidence of shape is not available, and the best use must be made of other characters: the low refractive indices (for the pure mineral γ , 1.537; α , 1.533); the very weak birefringence (0.004); the uniaxial, negative character; feeble cleavage traces to which extinction is straight; and the associates in the rock. Nepheline is usually accompanied by the Na-Fe amphiboles and pyroxenes such as riebeckite and aegirine; while it commonly occurs with, and shows alteration into, cancrinite.

Finally, nepheline gelatinizes with weak acid, in which condition it readily takes a stain such as fuchsine, which serves not only to differentiate between it and other optically-similar minerals, but also emphasizes zoning which may be practically invisible in the untreated slide.¹

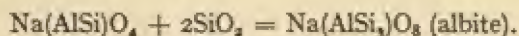
Nepheline is prone to alteration, and in some rocks has been replaced by an aggregate of white mica (in the so-called liebenerite pseudomorphs), by zeolites (natrolite is the most appropriate, judging from its composition), or by cancrinite. The latter is most distinctive (see p. 101), and very useful, for by its presence it may confirm doubtful diagnoses of nepheline.

The Role of Nepheline in Igneous Rocks.

Nepheline occurs in rocks characterized by an abundance of alkalis and alumina, but low in silica. Thus it is never found in

¹ Shand, S. J., "Staining of Feldspathoids and on Zonal Structure in Nepheline," *Amer. Min.*, xxiv (1939), p. 508.

Acid rocks, but may be abundant in those of Intermediate to Basic composition. In an acid magma containing potential free silica combination takes place between the components of nepheline and the silica, thus:—



Consequently nepheline tends to take the place of albite in magmas deficient in silica, and in certain types of nepheline-syenites, for example, all the felsic mineral may be nepheline. In hand-specimens of nepheline-syenites and nepheline-gabbros the mineral may be more obvious even than in thin slice, particularly on weathered surfaces. In certain examples from near Pretoria, South Africa, the rock-surfaces have been naturally etched; the white feldspars and black coloured silicates stand in strong relief to the euhedral nephelines up to half-an-inch across, which have been weathered-in, but show their characteristic shapes. In fresh specimens the nephelines are grey, with a rather silky texture and greasy lustre; but weathering develops a strong red or reddish-brown colour.

Among the Intermediate lavas, a well-characterized type is phonolite (p. 250 and Fig. 102); while among the Basic lavas nepheline occurs in tephrites and basanites. The term nephelinite is applied to similar lavas in which the nepheline is unaccompanied by feldspar of any kind (Fig. 125).

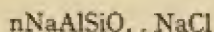
Three other members of the Feldspathoid group of minerals are often associated with nepheline and are closely related to the latter in chemical composition. They are sodalite, nosean and hauyne.

Sodalite.—Sodalite is a cubic mineral which is normally seen as grains or interstitial patches in certain types of nepheline-syenites. Occasionally it ranks as an essential mineral and then may be seen to form bright blue patches in the hand-specimen.

In this section sodalite is invariably colourless, and is best examined with the diaphragm carefully adjusted, when a Becke test will show results consistent with a particularly low refractive index (1.48). This is considerably lower than the indices of the feldspars and nepheline with which the sodalite is normally associated. Under the same lighting conditions the sections will show traces of an imperfect dodecahedral cleavage. Between crossed polarizers the mineral is, of course, isotropic.

On account of its rather negative characters, sodalite is never easy to identify with certainty, and in some cases a micro-chemical test is necessary. Small quantities of the mineral have been discovered in certain rocks by using ultraviolet light, when sodalite exhibits a brilliant yellow fluorescence.*

The exact composition is rather doubtful: it may be represented by the following formula:—



Nosean or **Noselite** is also cubic, and crystallizes in the same form as sodalite, *i.e.*, the rhombdodecahedron. The crystals are commonly very light yellowish-grey in thin section, and although they may show the characteristic six-sided sections to be expected on account of the crystal form, they are often strongly corroded, with a heavy dark margin (Fig. 48). As the refractive index is low (1.490) negative surface relief is exhibited. Curious canal-like



FIG. 48

Sections of nosean from nosean-leucitophyre, Rieden, Eifel, showing effects of magmatic corrosion, the characteristic canal-like markings, trains of gas bubbles, dodecahedral cleavage and (*right*) schiller structure.

channels cross the surface, and traces of a dodecahedral cleavage can frequently be discerned.

Hauyne or **Hauynite**.—This mineral also crystallizes in the same form as sodalite and nosean—the rhombdodecahedron—and shows much the same features as the latter, in regard to shape, corrosion, and cleavage, but is distinctive on account of its pretty sky-blue colour in thin section.

As regards composition, again there is some doubt, but both are closely related to nepheline, and while nosean contains Na_2SO_4 , hauyne contains CaSO_4 , in both cases additional to the nepheline molecule. Actually natural specimens are intermediate between these two, owing to the interchangeability of Na and Ca.

Both nosean and hauyne are essentially restricted to fine-grained

nephelinic or leucitic rocks. The former occurs, for example, in the nosean-leucitophyre from Rieden in the Eifel (Fig. 48), and in the nosean-phonolite which forms the Wolf Rock off the Cornish coast. Hauyne is not uncommon among the leucitic lavas of the Roman volcanic province.

Cancrinite is related to nepheline in composition, and in a sense may be regarded as "nepheline-carbonate" with a rather doubtful formula, perhaps $3\text{NaAlSiO}_4 \cdot (\text{Ca}, \text{Na}, \text{H})\text{CO}_3$.

This mineral is Hexagonal, but rarely forms definite crystals. Occasionally it is a primary constituent of nepheline-syenites, and in so-called cancrinite-syenites is an essential component. More often it fills a minor rôle, as an alteration product of nepheline, or arises by reaction between the latter and included grains of calcite (see p. 243). In Britain cancrinite has been recorded from a pegmatitic facies of the rare pseudoleucite-bearing rock, borolanite, at Loch Borolan, Assynt.¹

Under the microscope it occurs usually in shapeless masses, either in, or marginal to, nepheline. It is colourless, with both refractive indices below balsam: $\alpha = 1.496$, $\gamma = 1.519$. It has a perfect prismatic cleavage, and as its birefringence is high (0.023) it may resemble muscovite, but is easily distinguished therefrom by its negative relief, by its associates, and by showing a uniaxial negative interference figure in conveniently orientated sections in convergent light.

Melilite.—This name is applied to a series of uncommon, somewhat complex silicates of calcium, aluminium and magnesium. Any one specimen may be regarded as having a composition that can be expressed in terms of the two end-members of the series, akermanite ($\text{Ca}_2\text{MgSi}_2\text{O}_7$) and gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$).

Melilite crystallizes in one of the less symmetrical classes of the Tetragonal system, but actually crystals are rare, and the student encounters the mineral in thin sections only.

Like leucite, melilite is essentially a constituent of certain basic lavas and dyke-rocks, notably rich in calcium. Melilite-basalt remains the only well-known rock containing appreciable amounts of this mineral, but it is rare. An interesting British occurrence of melilite-bearing rocks has been described from Scawt Hill in Co. Antrim, from the contact-zone of a Tertiary basaltic plug intrusive into Chalk-with-Flints.²

In thin section melilite is very distinctive. It occurs in the form of

¹ Stewart, F., *Min. Mag.*, xxvii (1941), p. 1.

² Tilley, C. E., "The Dolerite-Chalk contact of Scawt Hill . . .," *Min. Mag.*, xxii (1931), p. 439.

lath-shaped sections often with somewhat irregular corroded margins. On account of the moderately high refractive indices surface relief is strong, but the chief diagnostic feature is the birefringence. The typical interference colour is an abnormal inky blue, deeper in the central zones than in the marginal parts of the crystals—the cores may be nearly isotropic.

The genesis of melilite has been studied experimentally and is considered on a subsequent page.

MINERALS LARGELY SECONDARY AFTER FERRO-MAGNESIAN SILICATES

(a) THE CHLORITE-SERPENTINE GROUP

The minerals falling in this group are often regarded as belonging to two groups, the chlorites and the serpentines; but all these minerals are closely related in composition and in physical characters, so it seems best to consider them together. Treated thus, the serpentine minerals become end-members of the larger group. Fundamentally, they are hydrous silicates of aluminium and magnesium, with iron tending to replace both of the latter components. Actually the composition of an individual specimen is complex, but can be expressed in terms of the end-members of a variable series, the more important being:—

Antigorite (a serpentine) $(\text{OH})_4\text{Mg}_3\text{Si}_2\text{O}_5$, which is comparable with Ferroantigorite, in which all the Mg ions are replaced by Fe.

Amesite, in which Al replaces part of the Si, with the necessary adjustment of the valency— $(\text{OH})_4\text{Mg}_3\text{Al}_2\text{SiO}_5$; while

Daphnite is the corresponding iron-bearing member: $(\text{OH})_4\text{Fe}_3\text{Al}_2\text{SiO}_5$.

Winchell names thirteen members of the group, each with a definite range of composition, but their identification is a problem for the expert mineralogist. Therefore the present account is limited to the essential characters of the commoner members of the group.

As the name implies, the chlorites are typically deep bluish-green in colour, and often superficially resemble the micas, though they are softer (hardness, 2 to 3); they have a soapy "feel" in hand-specimens; and while they cleave readily, the cleavage flakes are not elastic like those of mica. Crystallographically also they resemble the micas in being apparently monoclinic but with pseudo-hexagonal symmetry.

Again like the micas, the chlorites are of the sheeted layer type as regards atomic structure, which accounts, of course, for their perfect

basal cleavage. The fundamental basis of the structure is a sheet of SiO_4 tetrahedra linked into a repeating hexagonal pattern, like that illustrated for the micas in Fig. 27. The arrangement of the atomic sheets is polar, however, the stack illustrated in Fig. 28 being repeated below the horizontal plane, instead of being reflected across it, as in the micas.

Antigorite and **Chrysotile** are apparently dimorphous forms of the same serpentine mineral, the composition of which may be written thus:— $(\text{OH})_6\text{Mg}_3\text{Si}_4\text{O}_{10}$.

The difference between the two forms is one of habit: antigorite is lamellar, while chrysotile is fibrous, and when the fibres are of adequate length, is exploited as one of the forms of commercial asbestos.

In thin section they are pale green, with moderate refractive indices; $\gamma = 1.571$ and $\alpha = 1.560$. Thus the birefringence is weak, 0.011 or less.

These two minerals make up the greater part of serpentinites—serpentine rocks—having been formed from olivine, orthopyroxene (when the pseudomorphs are termed "bastite") and other ferromagnesian silicates.

Penninite is one of the commoner chlorites, being a widely-distributed alteration product of micas, amphiboles and pyroxenes. Penninite is an iron-poor chlorite, relatively deficient in aluminium, and may be expressed as dominantly $\text{Ant}_{50-80}\text{Am}_{40-20}$. It is the chlorite nearest in composition to the serpentine antigorite. It may be noted that some of the Al ions occupy positions in the structure that are normally filled by silicon: *i.e.*, they lie in the centre of tetrahedral groups of four oxygens, and should be regarded as proxy-aluminums. In thin section the mineral appears light green and slightly pleochroic. Frequently it is fibrous, and shows a radial to spherulitic structure. With indices $\alpha = 1.575$ and $\gamma = 1.576$, the birefringence is very weak—0.001. The most distinctive feature, however, is the interference colour commonly described as "ultra-blue." It is a deep inky blue usually, but deep brown, or rich violet are also sometimes exhibited. As the acute bisectrix, Z , is perpendicular to 001, and therefore to the cleavage traces, all sections showing the cleavage traces will prove to be fast along the cleavages.

Clinochlore or **Clinochlorite**.—This chlorite has the same limited iron-content as penninite, but is richer in Al. The composition may be expressed $\text{Ant}_{50-40}\text{Am}_{40-50}$, that is, about equal amounts of the antigorite and amesite molecules. The general optical orientation is the same as penninite but clinochlorite may show slightly oblique extinction (2 to 9°) measured to the cleavage traces, hence the name of the mineral. The surface relief is much the same

as for penninite, but the birefringence is slightly greater (0.004 to 0.011). The most distinctive feature, however, is repeated twinning on the mica law.

Iddingsite and Bowlingite.—In certain types of basaltic rocks the olivine phenocrysts are partially or completely converted into a strongly coloured yellowish or reddish-brown lamellar mineral, known under one of the above names. Their exact composition seems uncertain, but they are certainly highly ferruginous hydrous silicates, which are themselves easily altered into limonitic pseudomorphs.

Iddingsite is slightly pleochroic; it has strong surface relief (average values of α and γ being 1.702 and 1.743 respectively); and strong birefringence, though the high order interference colours are masked by the strong absorption.

It appears probable that there is no fundamental difference between the minerals covered by these two names.

Chlorophaeite.—Under this name a strongly coloured chloritic mineral has been described from certain of the basaltic and doleritic rocks of Carboniferous age from the Midland Valley of Scotland. Its most distinctive feature is a rich green colour when fresh; but it is prone to very rapid oxidation when it turns brown.

(b) TALC

This mineral resembles the chlorites and micas in having an atomic structure of the extended sheet type, which imparts the usual perfect basal cleavage and pseudohexagonal symmetry. Since the linkage between the atomic sheets is exceptionally weak, the latter readily slide over one another, and consequently talc is used as a "dry" lubricant. It is exceedingly soft, being the indicator mineral for "hardness 1" on Mohs' scale; while a soapy feel is a characteristic feature—the popular name for massive talc (steatite) is soapstone.

Talc is a hydrated silicate of magnesium and may be represented by the formula $(\text{OH})_2\text{Mg}_3\text{Si}_4\text{O}_{10}$. It is produced by the alteration of magnesium-rich silicates, and is typically found in metamorphosed ultrabasic and basic igneous rocks. One well-known mode of occurrence is the so-called actinolite-talc schist, in which the talc acts as matrix to the actinolite crystals. The mineral occurs, too, in serpentinites, and in these and all other occurrences there is a distinct resemblance to white mica in thin sections. The optical orientation of talc is the same as white mica, with the optic axial plane parallel to (100), and the acute bisectrix, X, perpendicular to (001). Thus the sign is negative but positive elongation is shown in all vertical sections. Further, the refraction ($\gamma = 1.575$ to 1.590, $\alpha = 1.538$ to 1.545) and double refraction* (0.030 to 0.050) are similar to white

mica. In spite of these resemblances to white mica, particularly to sericite, there is no risk of confusion, for the associates of the two minerals are entirely different: white mica is characteristic of acid rocks, while, as noted above, talc occurs in basic and ultrabasic assemblages.

(c) THE CARBONATE GROUPS

There are two important series of carbonates, named after the crystalline forms of CaCO_3 : firstly, the dominant Calcite Group, in which all the species crystallize in the Trigonal System; and secondly, the Aragonite Group, of the Orthorhombic carbonates. The latter are very rarely found in igneous rocks, and for this reason they will not receive further consideration here. Even the rhombohedral carbonates of the calcite group play a very subordinate rôle in igneous rocks, despite their great importance in sedimentary rocks.

In atomic structure the minerals of the carbonate groups differ fundamentally from all those so far considered, in that they contain complex radicles or groups of atoms in which the spacing is much closer than that which would be deduced from the atomic radii. Thus each carbon atom is in more than close contact with three oxygen atoms which form a single inseparable unit, the CO_3 radicle. The presence of the latter is characteristic of the carbonate group, and in calcite, for example, the atomic structure involves the regular grouping of Ca atoms and CO_3 radicles. As carbon is tetravalent, there is a residual charge of two units on each CO_3 group, which is balanced out by the addition of Ca, Mg, Fe or Mn.

The chief minerals in the group are tabulated below:—

		γ	α	$\gamma - \alpha$
Calcite	CaCO_3	1.658	1.486	0.172
Magnesite	MgCO_3	1.700	1.509	0.191
Siderite	FeCO_3	1.875	1.633	0.242
Dolomite	$\text{CaMg}(\text{CO}_3)_2$	1.680	1.501	0.178
Ankerite	$\text{Ca}(\text{Mg, Fe})(\text{CO}_3)_2$	—	—	—

Analyses show that there is a considerable degree of miscibility between the various end-members, and also with MnCO_3 (rhodochrosite).

Calcite shows a greater variety of crystal habits than any other mineral. The combinations of forms include hexagonal prisms, basal pinacoid, acute, unit and obtuse rhombohedra, and the very characteristic "general form," the scalenohedron, $(21\bar{3}1)$. Except the first two, all of these may occur as simple forms. Popular names have been given to some of these habits: thus crystals formed dominantly of the scalenohedron are termed "dog-tooth spar"; while "nail-head

spar" is a type of crystal combination terminated by the obtuse rhombohedron. In igneous rocks the finer points of the crystallography of calcite are of little significance, since the mineral is almost invariably of late, and generally secondary, origin, and therefore occurs in anhedral grains and aggregates.

The characteristic and almost sole form exhibited by the other members of the group is the unit rhombohedron; but commonly the faces of the crystals are composite and strongly curved, giving them a very characteristic saddle-shaped appearance.

Apart from their crystallographic characters, the outstanding feature of the rhombohedral carbonates is their perfect cleavage, parallel to the faces of the unit rhombohedron (1011).

In thin sections it is impracticable to differentiate between the several members of the group by ordinary methods, but it is relatively easy to do so using microchemical tests which are described in the appropriate text-books on petrographic methods. As is shown in the above table, the double refraction is outstandingly strong. Therefore in sections of normal thickness they polarize in high order colours and often appear dappled with very "watery" pink and green. In calcite, one of the indices is below, the other well above that of Canada balsam, so that any section of the mineral (other than the basal one which is, of course, singly refracting), changes in appearance as it is rotated over the polarizer. In certain positions the refractive index of the light passing through it will equal that of the balsam, so that the calcite practically disappears. When turned through a right angle, however, the outline becomes bold and the surface relief strong. Thus the rapid appearance and disappearance of strong surface relief on rotation of the stage constitutes a unique test for calcite.

The carbonates are characteristic weathering products of igneous rocks, particularly the more basic ones. In extreme cases little but the original texture remains: all the component minerals have been replaced by calcite, with small amounts of other secondary minerals. Normally calcite arises by weathering or hydrothermal alteration of calcium-rich silicates, notably the more basic plagioclases. In addition, calcite is a very common associate of zeolites, chlorite, chalcodony, etc., in vesicles and amygdules.

In two groups of rocks the presence of carbonates is of special significance. In some nepheline-syenites calcite occurs and has all the appearance of a primary mineral: it occurs in anhedral grains surrounded by and embedded in other primary minerals, that thus appear to be of later formation. This fact is significant in connection with the problem of the origin of this type of igneous rock, and is more fully considered in due course. Intrusive veins, dykes and

plugs of carbonate are not uncommon in nepheline-syenite complexes (see p. 243), and are known as carbonatites.

Those peculiar rocks collectively known as lamprophyres also contain carbonate in notable quantities, often sufficient to cause effervescence with dilute acid. In this case the carbonates appear to be of deuteric origin (p. 175); they are found not only widely dispersed in the groundmass of the rocks, but also form pseudomorphs after olivines. In such cases it may be questioned if the carbonate is really calcite: it might be expected to be magnesite.

Although ore formation is beyond the scope of this book, it is appropriate to mention that the carbonates here considered are widely distributed in mineral veins, and are typical gangue minerals—witness the many beautiful specimens of well-crystallized fluorite, calcite, dolomite and quartz associated with blende and galena that are prominent in all mineral collections.

MINERALS LARGELY SECONDARY AFTER ALKALI-ALUMINOSILICATES

(a) THE ZEOLITES

The zeolites constitute a group of hydrated silicates of aluminium, with Na, K, Ca or rarely Ba, and therefore are closely linked with the feldspars in chemical characteristics. In large measure they are produced from the latter and from the feldspathoids by hydrothermal alteration. This relationship is emphasized by the ease with which zeolites revert to feldspars under the impetus of thermal metamorphism. A common mode of occurrence is as infillings of amygdales and vesicles in altered lavas, and many fine specimens in mineral cabinets come from such occurrences.

The zeolites are almost unique by reason of the ease with which they part with the loosely held water of crystallization. This property gives the group its name (from *zeo*—I boil), as on heating the water is evolved violently. They are noteworthy again on account of the ease with which base-exchange may be effected. This property is exploited in the process of water-softening, though artificial zeolites are used, as natural ones do not occur in sufficient quantities.

Crystallographically the zeolites are interesting as providing good examples of pseudosymmetry. Careful measurement shows that many crystallize in systems other than those which would be selected after superficial examination. Thus among the commoner zeolites some are nearly Tetragonal, others nearly Rhombohedral, several appear Orthorhombic but are actually Monoclinic. The effect is often enhanced by complex twinning. For example, a Monoclinic zeolite, in the untwinned form not unlike a feldspar in general

appearance, may assume the external form of a Cubic rhombododecahedron. In short, the zeolites tend to shake one's faith in crystallography.

Although some of the zeolites are best left to the expert for exact determination in thin section, they serve to illustrate certain aspects of micro-petrological technique, and these are emphasized in the following account.

For purposes of description we consider together certain zeolites which have a distinctly fibrous habit.

The Fibrous Zeolites.

(i) **Natrolite**.—As the name suggests this is a sodium-aluminium zeolite, and therefore chemically related to both albite and nepheline. When the individual crystals are sufficiently well developed to show their terminations, they give the impression of being much-elongated Tetragonal prisms with bipyramidal ends. Actually they are Orthorhombic, but the ratio of $a : b$ is 0.978 to 1—very close to the 1 : 1 Tetragonal ratio. The distinctive optical characters include negative surface relief, as both indices are well below Canada balsam ($\alpha = 1.476$, $\gamma = 1.488$). The birefringence (0.012) is therefore a little above that of quartz. The acute bisectrix, Z , is coincident with the axis of elongation, therefore *all* prismatic sections must show a slow vibration parallel to the length. This is sometimes concisely stated thus: the crystals are "length—slow."

(ii) **Scolecite**.—This is a calcium-aluminium fibrous zeolite, which is therefore analogous with anorthite among the feldspars. This mineral also is pseudosymmetrical, as, although it is Monoclinic, the angle β is close to a right angle— $90^\circ 42'$ only. It is more distinctive in the optical than in the crystallographic sense, as the acute bisectrix X makes an angle of 15° with the axis of the crystal. In this case the crystals are "length—fast," of course. Both indices are below that of balsam ($\alpha = 1.512$, $\gamma = 1.519$). The maximum birefringence, 0.007, is almost indistinguishable from that of quartz.

(iii) **Thomsonite** is Orthorhombic, but pseudotetragonal, as the $a : b$ ratio is 0.993 : 1. Again the crystals are elongated parallel to the c -axis, and vary in habit from prismatic to fibrous or lamellar. The cleavages are pinacoidal, that parallel to (010) being perfect. The most useful optical character is the orientation of the optic axial plane, which is parallel to (001), and therefore at right angles to the length. As the optic normal coincides with the axis of elongation, some of the prismatic sections will be length—slow, but others length—fast.¹ Otherwise thomsonite resembles the other fibrous

¹ It must not be assumed that thomsonite is the only zeolite which displays this feature. Mesolite, another Na-Ca zeolite of finely fibrous habit, is also elongated along Y and therefore has positive-negative elongation.

zeolites in having refractive indices below balsam; but the birefringence varies somewhat with the composition, and may reach 0.020, though a lower value—about 0.013—would be more appropriate for a zeolite. Even so, the interference colours may range through the more brilliantly coloured upper half of the first order of Newton's scale.

All the fibrous zeolites are composed of SiO_4 tetrahedra linked into chains which are aligned parallel to the principal axis of the crystal. In natrolite there are five tetrahedra in each link of the chain, therefore the formula is based on 5SiO_2 . In all zeolites, however, a proportion of the silicons are replaced by proxy-aluminums, as in certain other minerals already considered. Thus in natrolite 5SiO_2 becomes $(\text{Al}_2\text{Si}_3)\text{O}_{10}$. To restore the valency balance, cations must be added, and the complete formula is $\text{Na}_4(\text{Al}_2\text{Si}_3)\text{O}_{10} \cdot 2\text{H}_2\text{O}$.

Scolecite is similar, except that Ca takes the place of Na_4 . Mesolite is so named as it occupies a middle position between natrolite and scolecite; while thomsonite also contains both Ca and Na. In this case, in order to maintain the balance, readjustment of the ratio of silicons to aluminums is necessary, and (CaAl) takes the place of (NaSi) . The formula is still of the type $n(\text{SiO}_2)$, but $n = 40$, and the composition is represented by $\text{Na}_3\text{Ca}_9(\text{Al}_{21}\text{Si}_{19})\text{O}_{80} \cdot 24\text{H}_2\text{O}$.

A second important group includes stilbite, heulandite, phillipsite and harmotome of altogether different habit from the preceding. **Stilbite** and **Heulandite** often occur together in beautiful crystal groups. Both may be colourless, cream or pink; both show striking differences in lustre, that on the (010) faces being pearly, while all the other faces are equally glassy-looking. This results from a perfect cleavage parallel to the side-pinacoid, and probably these minerals have a sheeted, instead of a chain-structure. Stilbite forms very distinctive groups of crystals, pinched in at the middle like a sheaf of wheat. Heulandite, on the other hand, occurs in well-formed Monoclinic crystals of coffin-like shape, the "lid" being the pinacoid (010). The crystallographic difference is readily checked by an optical test. The optic axial plane is perpendicular to (010) in heulandite, and the acute bisectrix, Z , emerges at right angles to this face and to the cleavage. In stilbite, however, the optic axial plane is parallel to (010). Therefore the examination of a cleavage flake in convergent light will immediately afford a means of distinction.

Both stilbite and heulandite are Ca-Na zeolites, and therefore related in composition to mesolite and thomsonite, but differ from these in the proportions of the several components.

Phillipsite provides an example of pseudosymmetry carried to the limit: it is possibly Triclinic, certainly not more symmetrical

than Monoclinic; but it is invariably twinned and looks to be at least Orthorhombic, often Tetragonal and in extreme cases, Cubic. The twinning is the chief diagnostic feature under the microscope, though it is not unique in this respect and the optical orientation must be checked to distinguish it from the much rarer harmotome. Phillipsite occurs as an alteration product of feldspars of the appropriate composition; but in addition is deposited by hot springs and occurs also in the red clay of the oceanic deeps.

Phillipsite contains both K and Ca—a condition impossible in a homogeneous feldspar, but common among the perthites, of course. In 12SiO_2 half the silicons are replaced by proxy-Al's, while the ratio of K to Ca is variable.

Finally, **Harmotome** is included as an example of a zeolite containing barium, and therefore related to, and derived by alteration from the barium-feldspars celsian and hyalophane. The crystals usually occur as very distinctive cruciform twins.

Analcite or Analcime.—Although analcite may be considered as closely related to the feldspathoids, as it contains loosely held water of crystallization (which links it with the zeolites), it is convenient to consider it here. It crystallizes in the Cubic system, the only common form being the icositetrahedron, though rarely the cube occurs in addition. Usually the crystals are dead-white, but they are sometimes tinged with pink, and rarely may be colourless and quite transparent.

Analcite is a hydrated silicate of sodium and aluminium, essentially $\text{NaAlSi}_3\text{O}_8 \cdot \text{H}_2\text{O}$. In its degree of silication, therefore, it is comparable with leucite. Artificial analcite readily exchanges its Na-atoms for K, Ag or Rb, for example. In this connection it is significant that K-analcite occurs as phenocrysts in lavas in Montana,¹ and on the other hand that analcite occurs as an alteration product of leucite, *e.g.*, in East Lothian, Scotland. As might be anticipated, there is no difference between the X-ray patterns of K-analcite and leucite.

In thin section analcite may be a difficult mineral to identify with certainty, on account of its rather negative characters. Typically it is quite colourless, with low surface relief consistent with its low refractive index (1.487). Careful manipulation of the iris diaphragm will often cause the sections to display cubic cleavage. Sometimes, as one would expect from its crystal characters, it is perfectly isotropic; but often it exhibits optical anomalies, such as weak birefringence (about 0.002) and complex twinning, in a manner somewhat reminiscent of leucite. In weathered rocks analcite is represented by turbid alteration products, and in such cases positive identification is impracticable.

¹ *Bull. Geol. Soc. Amer.*, lv (1944), p. 445.

In British rocks analcite is widely distributed especially in the Intermediate and Basic intrusives of Carboniferous age, notably teschenites and crinanites and in basaltic lavas of comparable composition. The mineral is probably most abundant in the so-called analcite-syenite, an example occurring at Howford Bridge, Ayrshire.

The associates of analcite in these rocks are ilmenite, labradorite, lilac-coloured titanaugite, and red-brown barkevikite. In all these rocks the analcite is a primary mineral, though of late formation. Therefore it normally occurs in interstitial patches between the earlier formed constituents; but with increasing amounts it spreads into the adjacent plagioclases along cleavages and veins, and progressively replaces them. This *analcitization* is a late-stage replacement comparable in its effects with albitization. At a still later stage, solutions from which analcite can crystallize percolate into steam cavities, vesicles and geodes, and euhedral crystals in mineral collections come from the linings of such cavities.

The importance of analcite in petrogenesis lies in the fact that magma containing it in any quantity is of notably low viscosity, and therefore particularly prone to show the effects of differentiation through density stratification.

(b) THE EPIDOTE GROUP

This group of minerals comprises the Orthorhombic zoisite, and the Monoclinic clinozoisite, epidote (pistacite), piedmontite and orthite (allanite).

The composition of zoisite may be represented by the formula $(\text{OH})\text{Ca}_2\text{Al}_2\text{Si}_2\text{O}_{12}$. If any iron replaces aluminium, the substance tends to crystallize in the Monoclinic system, as clinozoisite. The latter is one end member of a continuous series, the other being the hypothetical "iron-epidote" $(\text{OH})\text{Ca}_2\text{Fe}_2\text{Si}_2\text{O}_{12}$. If the latter does not amount to more than 10 per cent of the whole, the mineral is clinozoisite; if between 10 and 40 per cent, the term epidote is applied. No natural epidote contains more than 40 per cent of the iron-bearing component. Two members of the group are notably rich in manganese: thulite is a manganiferous zoisite; while piedmontite is a manganiferous epidote with the formula $(\text{OH})\text{Ca}_2(\text{Al}, \text{Mn})_2\text{Si}_2\text{O}_{12}$. The variety withamite is a poorly manganiferous piedmontite. Finally allanite, sometimes called orthite, is essentially a variety of epidote containing the rare elements cerium and yttrium.

Clinozoisite—Epidote.—All Monoclinic members of the group occur in crystals elongated along the *b*-axis, and difficulty is experienced in sorting out the faces in the principal zone parallel to this direction. Commonly the basal pinacoid (001), orthopinacoid (100) and a hemiorthodome (101) occur in this zone, and while some of

the faces are strongly striated in characteristic fashion, others may be perfectly smooth and highly lustrous, while again others may be relatively dull. Two observations may be of assistance: the common type of twin, often betrayed by a re-entrant angle at the ends of the crystal, has the twin-plane parallel to (100), which may therefore be identified; while the cleavage is parallel to the basal pinacoid (001).

In its simplest development the end of the crystal of epidote shows the unit prism, with faces meeting in an edge parallel to the twin plane and to the face (100). Sometimes the crystals are terminated by a hemibipyramid; or by combinations of prisms and hemibipyramids.

Crystals of epidote may be nearly black, but usually are of a distinctive shade of yellowish green, termed pistaccio green, hence the synonym, pistacite. The darker coloured crystals may bear a strong superficial resemblance to tourmaline; but, unless they are too thick, may be readily distinguished by the different absorption of light in different directions perpendicular to the principal crystallographic axis of epidote. Tourmaline, of course, can show no such differences in this zone.

Optical Properties.

The optical and other physical properties vary systematically from clinozoisite to ferriferous epidote. The minimum and maximum refractive indices and the birefringence are tabulated below:—

	clinozoisite	ferriferous epidote
α	1.725	1.732
γ	1.740	1.781
birefringence ($\gamma - \alpha$)	0.015	0.049

Thus the highest interference colours in a slide of normal thickness (30 microns) should be a pale third order yellow for iron-rich epidote. The value of the birefringence rises rapidly with increasing iron content. When the latter is low, the sections are colourless; but increasing iron causes a light yellow colour and slight pleochroism. A noteworthy feature of epidote and other minerals in the group is the noticeable variability in birefringence even within the limits of a small crystal. The birefringence of clino-zoisite is notably anomalous, on account of strong dispersion: the interference colours are rich dark-blue or brown, like those of penninitic chlorite.

The plane of optical symmetry (optic axial plane) is perpendicular to the length of the crystal, therefore all sections lying with the principal crystallographic *b*-axis in, or parallel to, the plane of the slide, will exhibit straight extinction. Sections cut perpendicular to the length, however, show oblique extinction up to 30 degrees

measured between the slow vibration direction (Z) and the traces of the 001 cleavage.

The optical orientation of epidote is such that one optic axis emerges at right angles (approximately) to the (100) face, on which a detrital grain or small crystal will normally lie; while the other optic axis is almost perpendicular to the basal cleavage. Therefore the distinctive optic axis figure appropriate to such a section is seen in convergent light both in crystals of normal habit and in cleavage flakes.

Piedmontite is a strongly coloured mineral in thin section and has a spectacular pleochroism scheme:—

- X — the fast vibration — lemon yellow;
- Y — — amethyst to pale violet;
- Z — the slow vibration — vivid red.

As the crystals are normally thin prisms much elongated along the principal *b*-axis, corresponding with the Y-vibration, some prismatic sections change from amethyst to lemon, while others change from amethyst to bright red. Sections across the length of the prisms, of course, vary from lemon to bright red. In view of this distinctive pleochroism, confirmatory tests are scarcely necessary; but it should be noted that the pleochroism of the manganese-bearing zoisite (Orthorhombic) is the same, but in reverse:¹ X is red, and Z, lemon-yellow.

Allanite or **Orthite** is also distinctively coloured in thin section, and strongly pleochroic, from buff to deep red-brown. Twinning, usually simple, is common on the usual epidote plan. Identification of allanite is aided by its common association with another member of the epidote group—sometimes even in zonal association.

Mode of Occurrence and Origin.

Excluding zoisite, all the chief members of the group are produced by, and characteristic of, a mild degree of dynamothermal metamorphism, in the course of which both coloured silicates and the anorthite-component of plagioclase break down into new stable associations, prominent among which is a member of the epidote group. Plagioclase may be represented by perfect pseudomorphs consisting of packed aggregates of narrow prisms in slightly divergent groups; or the central parts of a large crystal may be composed of similar crystals or granular aggregates, embedded in, and surrounded by, albite.

¹ Owing to the strong absorption, it is often difficult or impossible to check the character of the vibration, whether fast or slow, in the usual manner using a quartz wedge.

The clinozoisite molecule may be regarded as a high-density representative of anorthite. Obviously, unless there has been an actual influx of Fe ions, anorthite can be replaced only by zoisite or clinozoisite (typically the latter). Similarly, both common augite and hornblende contain the components of epidote, and the latter is produced, usually in association with chlorite, under the conditions that result in the replacement of anorthite. This type of replacement is often termed **epidotization**.

In addition to this secondary development, *primary* epidote occurs in some pegmatites, and less frequently even in granites and other normal igneous rocks.

Piedmontite is essentially a component of crystalline schists, the best examples probably coming from Japan. Withamite has been recorded from Britain—it occurs in vesicles and veins in an andesitic lava from Glencoe, Scotland.

In many other "altered rocks" epidote and its varieties may be abundant, in areas which have demonstrably not been subjected to regional metamorphism. In such cases the mineral is probably of deuteric origin, and derived ultimately from the normal dark minerals—micas, amphiboles and pyroxenes in rocks.

(c) SCAPOLITE GROUP

The minerals of this group are aluminosilicates of calcium and sodium, with chlorine, or a carbonate or sulphate radicle in addition. They are thus fundamentally related to the plagioclase feldspars, of which they are, in fact, alteration products, and like them, they form a continuously variable series. The end members of the series are:—

Marialite, $\text{Na}_4\text{Al}_3\text{Si}_2\text{O}_{24}\text{Cl}$, which may be written $3\text{Ab} \cdot \text{NaCl}$; and

Meionite, $\text{Ca}_4\text{Al}_3\text{Si}_2\text{O}_{24}(\text{CO}_3)$, which may be written $3\text{An} \cdot \text{CaCO}_3$.

As in the feldspars, CaAl is progressively substituted for NaSi , while the carbonate or sulphate radicle (CO_3 or SO_4) may be substituted for Cl . These end members are comparatively rare, and the scapolite which most commonly occurs lies between Ma_{20} and Ma_{30} (mizzonite).

The scapolites crystallize in the Tetragonal System and may occur as striated prisms, but often the mineral is massive. Vertical cleavages are well developed, parallel to the prism (110) in some species, to the pinacoid (100) in others, while both are sometimes developed.

Naturally the optical properties vary with the composition: both refractive indices and birefringence increase as the proportion of meionite increases. Mean values for the refractive indices are:— $\alpha = 1.55$, $\gamma = 1.58$, giving a maximum birefringence of 0.03. Thus for some scapolite the surface relief and birefringence may be

little different from quartz; but generally while the refringence is low to moderate, the birefringence may be sufficiently high as to cause bright second order interference colours in vertical sections. In basal sections the prismatic cleavage traces are well displayed, and such sections yield a negative uniaxial interference figure.

In igneous rocks scapolite is secondary after feldspar, and a volcanic environment where plagioclase-bearing rocks are liable to alteration by solfataric or fumarole activity is indicated by the chemical composition of these minerals. Much scapolite is metamorphic, however, and arises during the thermal metamorphism of limestones in which it is accompanied by such minerals as diopside, sphene, etc., as in the Deeside Limestone of Dalradian age in Aberdeenshire.

(d) KAOLINITE

Kaolinite is one of several "clay minerals" whose systematic study has only really advanced since the application of X-ray

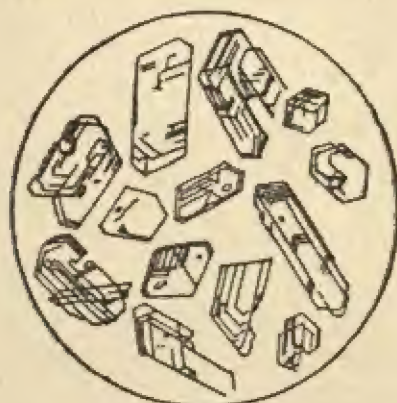


FIG. 49

Crystals of kaolinite, under the microscope. (After Teall.)
Very highly magnified.

techniques, for all of them are so finely crystallized that ordinary microscopic examination is of little avail. An account of the clay-minerals as a whole is inappropriate here, but this one important example has been selected because it is a characteristic alteration product of the feldspars (see p. 210).

Kaolinite is one of three clay minerals having the formula $(\text{OH})_3\text{Al}_2\text{Si}_2\text{O}_{10}$. The Si-O atoms are arranged in the extended sheet pattern of the micas, talc, etc. From this it may be anticipated that it has a pseudo-hexagonal (actually Monoclinic) symmetry, and perfect basal cleavage (Fig. 49). Individual flakes are too minute to

be examined separately, and in aggregate they have some resemblance to finely crystalline sericite—a similarity that is strengthened by the fact that both are secondary after feldspar. Kaolinite, however, has a double-refraction close to that of quartz and therefore much lower than that of sericite. Kaolinite gives its host feldspar a characteristic clouded appearance, and in hand-specimen the feldspar may eventually become white and opaque.

ACCESSORY MINERALS: NORMAL ACCESSORIES

(a) GARNET GROUP

The garnets are silicates of aluminium, iron, manganese, chromium, calcium and magnesium. The crystal structure consists of separated SiO_4 groups, and there are three of such groups in the unit of the structure, giving Si_3O_{12} which appears in all the formulæ. In this structure there are twelve free links to which other atoms are attached according to the scheme:

$\text{M}''_3\text{R}'''_3(\text{Si}_3\text{O}_{12})$, where M is a divalent, and R a trivalent element. The following varieties may be distinguished:

	<i>Formula</i>	<i>Colour</i>	<i>Refr. Index</i>
Pyrope	$\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	blood red	1.705
Almandine	$\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	dark red	1.830
Spessartine	$\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	red	1.800
Uvarovite	$\text{Ca}_3\text{Cr}_2\text{Si}_3\text{O}_{12}$	green	1.870
Grossularite	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$	green or orange-red	1.735
Andradite			
(Melanite)	$\text{Ca}_3\text{Fe}_2\text{Si}_3\text{O}_{12}$	black	1.895

These are largely hypothetical: natural garnets are more complex in composition than any of these "pure" garnets and in any specific case may be regarded as containing *either* the first three, *or* the second three components in varying proportions. Thus a common red garnet on analysis would be found to contain Mg'' , Fe'' and Mn'' , and according to the amounts present might be expressed in terms of the molecular percentages of Py, Al and Sp respectively. Both groups of three form continuously variable series, but grossularite, for example, does not mix with pyrope.

Crystallographically the garnets appear to be simple: the only forms occurring normally are the rhombdodecahedron (110), the icositetrahedron (211) and much less commonly the hexakis octahedron (321). Garnets of the Py.Al.Sp. type are isotropic in thin section, and there seems no reason to doubt their full Cubic symmetry; but those in the second group frequently exhibit optical anomalies. The examination of the optical characters suggests that

the apparently simple crystals are actually complex twins consisting of twelve or twenty-four individuals, which are biaxial and may be Orthorhombic. Above 800°C they assume Cubic symmetry.

In thin section all garnets are characterized by high relief, on account of the high refractive indices; but the figures quoted above must be regarded as approximations only, on account of the complex composition of natural garnets. As might be expected, the sections often exhibit zoning, reflecting changes of composition during growth. No cleavages occur in garnets in rocks; but detrital garnet separated from sands frequently shows a good dodecahedral cleavage developed as a consequence of severe pounding by wave action. Garnets alter in a variety of ways. Thus in rocks which have suffered contact metamorphism, garnet may be pseudomorphed by cordierite. The commonest alteration product is probably chlorite; but garnet carrying titanium (schorlomite) may alter in part into sphene.

Undoubtedly the finest crystals of garnet occur in, or have been obtained from, the metamorphic rock, garnet-mica-schist. But in



FIG. 50

Garnet: *Centre*, the simplest form, the rhombicuboctahedron (110); *left*, a section through centre of crystal, parallel to one of the axial planes of symmetry (100), (010), or (001); *right*, section through centre of crystal parallel to one of the twelve dodecahedral faces. Zoning is formally shown.

addition to this—the commonest—mode of occurrence, garnet may occur as a normal accessory in a wide range of igneous rocks. In acid dyke-rocks a garnet of the first group, often rich in manganese, occurs in this way. Intermediate rocks containing feldspathoids such as nepheline and leucite, not infrequently contain garnets near to melanite (andradite) in composition. As might be anticipated, accessory garnets are found in ultrabasic igneous rocks such as peridotites, and are rich in magnesium. They tend to survive, as distinctive red crystals, when such rocks are converted into serpentinites (see below). Grossularite has an entirely different mode of occurrence, and is almost restricted to calcareous sedimentary rocks which have suffered thermal metamorphism. Andradite, too, is characteristic of such an environment, and is prominent in the so-called skarns—lime-silicate rocks from intrusive contact-zones.

(b) SPINEL GROUP

The spinels crystallize in the holosymmetric class of the Cubic system, and it is rare to find forms other than the octahedron represented, though occasionally the edges of the latter are truncated by the rhombododecahedron (110). Twinning on the "Spinel Law" is not uncommon. In this the twin plane is parallel to an octahedron face; the twins are usually flattened parallel to the twin plane, so that the crystals have the aspect of flattened triangular tablets, with re-entrant angles at the corners.

In composition the spinels differ from the groups so far considered in that they are not silicates, but aluminates, ferrates, chromates, etc. The typical spinel most commonly represented in mineral collections is brilliant ruby-red in colour ("ruby-spinel") and on analysis would show equal molecular proportions of MgO and Al_2O_3 . The correct formula is therefore MgAl_2O_4 —magnesium aluminate.

In pleonaste some of the atoms of both Mg and Al in ruby spinel are replaced by iron, thus: $(\text{Mg}, \text{Fe}) (\text{Al}, \text{Fe})_2\text{O}_4$; while in hercynite the replacement has been carried to completion—Fe'' replaces Mg'', giving the formula FeAl_2O_4 .

Picotite is a spinel of very mixed composition, resembling pleonaste but with Cr replacing some of the Al, Fe atoms, thus: $(\text{Fe}, \text{Mg}) (\text{Cr}, \text{Fe}, \text{Al})_2\text{O}_4$. Chromite, FeCr_2O_4 , magnetite, $\text{Fe}''\text{Fe}'''\text{O}_4$ and gahnite, ZnFe_2O_4 , have this much in common: they are all three opaque both in the mass and in thin section.

Those spinels which occur in igneous rocks are strongly coloured: magnetite is quite opaque in the thinnest sections; chromite may be slightly translucent on the edges of the crystals and appear deep brown-black; while those of mixed composition may be deep green, rich coffee-brown or dark maroon.

The spinels are relatively rare accessory minerals in igneous rocks, but are much more abundant in certain types of metamorphic rocks. As might be expected from their chemical composition the spinels, excluding magnetite, are restricted to the ultrabasic igneous rocks, especially those of non-feldspathic type such as peridotites. Thus olivinites (dunites) contain many scattered octahedra of spinel, usually chromite, while enormous quantities of the latter mineral occur in the great Bushveld Complex in the Transvaal, South Africa, in thick layers that in some instances are nearly pure concentrates of the mineral, though usually the orthopyroxene, bronzite, accompanies it. These **chromitites**, as they may be called, are evidently swarms of crystals which, forming at high temperatures, sank through the magma by reason of their high specific gravity (Fig. 116).

Apart from such occurrences, however, spinels are typical consti-

tments of silica-poor aluminous hornfelses formed from argillaceous sediments by thermal metamorphism. In the presence of silica the aluminous spinels combine with the SiO_2 to form the silicate, cordierite. Frequently in thin sections the first indication of the presence of cordierite (a difficult mineral to identify), is the presence of the associated swarms of minute spinels. Again, magnesian limestones (including dolomites) on subjection to thermal metamorphism contain spinel, provided some alumina was available. A rock of this nature is the coarsely crystalline marble, charged with spinels of a pure ruby red colour, and of gemstone quality, occurring in Burma. A large proportion of the perfect crystals seen in mineral collections are obtained from such sources; but it may be noted that synthetic spinels, in a wide range of colours, can now be manufactured in quantity.

(c) TITANIUM-BEARING GROUP

(i) **Rutile, Anatase and Brookite.**—Rutile is the most stable of the three crystalline forms of TiO_2 —rutile, anatase and brookite—and is the one which most commonly occurs as an accessory mineral, especially in the more acid rocks. It forms slender Tetragonal prisms and needles which are frequently twinned to give geniculate and heart-shaped forms. Both in hand-specimens and under the microscope, rutile is coloured yellow or red. It is remarkable for its exceptionally high refractive indices (2.61 and 2.90), the highest for any of the normal rock-forming minerals.

Rutile occurs in crystalline schists and is also common in sands and sedimentary rocks. Fine hair-like crystals occurring in clay and slates (clay-slate needles) are referred to rutile. In pneumatolytized granites, rutile is often present as a product of the breakdown of complex titanium-bearing minerals, such as biotite and sphene. Under these circumstances it may form an interlocking structure of regularly orientated needles, known as sagenite. Quartz crystals in certain granites contain myriads of exceedingly minute needles believed to be rutile, by analogy with the megascopic, reddish-brown acicular crystals of more robust habit occurring in the quartz of certain pegmatites. Relatively large crystals also occur in eclogites.

Anatase, the second of the TiO_2 minerals, differs from rutile and brookite in crystallographic characters and optical properties. It crystallizes in the holosymmetric class of the Tetragonal system, and exhibits two different habits: (1) tabular, due to the strong development of the basal pinacoid, often modified on the edges or corners by feebly developed bipyramid faces; and (2) steep bipyramids, usually with well-developed surface markings (Fig. 51).

In thin section anatase is scarcely ever seen in ordinary rocks; but in granitic sands containing a natural concentrate of heavy constituents, it is often plentiful. The anatase tablets vary from colourless to rather dull shades of blue, green or brown. The refractive indices are very high (2.49 and 2.56), and the birefringence is also strong (0.07). In view of its distinctive appearance a confirmatory test is seldom necessary, but the tablets show a uniaxial (positive) interference figure in convergent light.

Brookite crystallizes in the Orthorhombic system, in platy-crystals with the pinacoid (100) well-developed, and showing strong vertical striations by reason of oscillation with the unit prism.

Again we turn to granitic sands, like those from Dartmeet on Dartmoor, to study typical crystals or grains. They are light yellow to brown in tint, with closely ruled striations as noted above. The really distinctive feature, however, is the failure to extinguish, on account of crossed axial-plane dispersion. The effect of this property

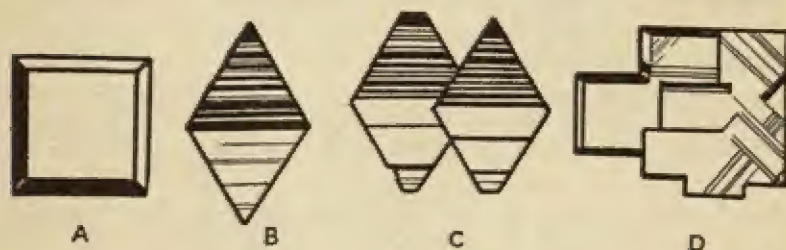


FIG. 51

Crystals of anatase: (A) and (D) of tabular habit, with characteristic surface markings in the latter case; (B) and (C) of bipyramidal habit, and in the latter case, two crystals in parallel growth.

is to cause the section to display a succession of interference colours, in the order of Newton's scale, when the stage is rotated with both polarizer and analyser in operation.

(ii) **Sphene or Titanite**.—Sphene is a silicate of titanium and calcium, CaTiSiO_5 , occasionally seen in mineral collections as small wedge-shaped crystals, but much better known as a distinctive and widespread accessory mineral in rocks of many different kinds. Sphene can sometimes be seen even with the naked eye, and easily with a lens, in hand-specimens of granodiorites, syenites and diorites, for example. The crystals, which belong to the Monoclinic system, are brilliantly lustrous and range in colour from light yellow to green or brown.

In thin section sphene may be colourless, but is commonly a shade of greyish-brown, and is slightly pleochroic. The refractive indices,

2.01 and 1.90, are notably high, so that surface relief is strong. The birefringence also is particularly strong, so that the interference colours are very light—the so-called “high order whites”—and these, superimposed on the normal absorption tint of the mineral, make no appreciable difference. Thus, provided the section is not in the position of extinction, crossing and uncrossing the “nicols” makes no difference to the colour of the section. This observation provides a unique test for the identification of sphene.

Although sphene is an almost constant accessory in igneous rocks it normally forms very small, scattered crystals; but a rock-type has been discovered in the famous Kola Complex consisting of crowded crystals of sphene embedded in a matrix of apatite—a truly extraordinary rock-type which does not fit easily into any standard scheme of classification.

In metamorphic rocks also sphene may occur abundantly. This is

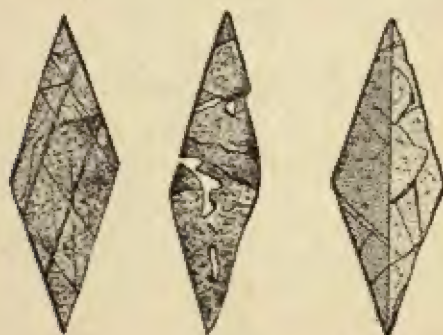


FIG. 52

Sections of sphene: two on left from ditroite, Ditro, Transylvania, one showing cleavages, the other, corrosion inlets; on the right a simple twin from leucite phonolite, Perlerkopf, Brohlthal.

the case, for example, in hornblende-schists and amphibolites, rock-types formed by the dynamothermal metamorphism of basic igneous rocks.

(iii) **Perovskite.**—Among the rarer accessory minerals perovskite fills an important rôle in some uncommon rock-types. It is calcium titanate, CaTiO_3 , and crystallizes in the Cubic System, the octahedron being the only form normally developed. The small crystals are isotropic, and Cubic beyond question; but larger crystals exhibit optical anomalies and, it is recorded, quite considerable birefringence. The outstanding optical property is a very high refractive index (2.38), which makes the small crystals stand out strongly, despite their size. In fact very small crystals have such a heavy

margin that they appear almost opaque. Cleavage is stated to be perfect, parallel to cube faces.

Perovskite is characteristic of, and restricted to, under-saturated lime-rich ultrabasic lavas, and is a constant associate of melilite in melilite-basalts, in which it occurs as small grey octahedrons and twinned groups. Probably the most notable occurrences so far described are in ultrabasic lavas from Uganda,¹ among which are some of special interest and importance as they contain the newly-discovered aluminosilicate of potassium, kalsilite. The perovskite in these lavas occurs in unusually large quantities, up to 6.2 per cent in one type.² In these rocks the perovskite is golden-brown, yellow or green instead of the commoner grey.

(d) IRON-ORE GROUP

The iron-ores that occur as constituents of igneous rocks are magnetite, titanomagnetite, ilmenite, pyrite and rarely pyrrhotite. The first three are normal accessories in a wide range of rock types, and in some cases occur in such amounts that they must be regarded as important essential components.

Magnetite.—This mineral is grouped with the spinels on account of its chemical composition and crystallographic characters. Although often written as Fe_3O_4 , in order to bring the formula into line with the other spinels, it should be written $\text{Fe}''\text{Fe}'''_2\text{O}_4$, and regarded as ferrous ferrate. Actually the ferrous iron may be replaced by Mn, Mg or Ni, while for the ferric iron Ti, Mn or Cr may be substituted in part.

Magnetite crystallizes in the Cubic System, and generally the only form represented is the octahedron, but the rhombododecahedron may be developed. As might be expected, spinel twins are not uncommon. Magnetite is invariably opaque, even in the thinnest sections, and in the absence of crystal form, it may not be easy to distinguish it from other opaque ores; but by oblique reflected light it has a characteristic steely metallic sheen. It is the most strongly magnetic of the iron-ores, and may be separated from the others by means of a bar magnet.

As regards mode of occurrence, magnetite is variable. In many igneous rocks, especially the more basic, magnetite is an accessory of early formation—the characteristic, often perfectly formed octahedrons occurring plentifully in thin sections of basalts and other lavas, are of this type; but in some basalts it is one of the

¹ Holmes, A., "A Suite of Rocks from South-West Uganda containing Kalsilite, a Polymorph of KAlSiO_4 ," *Min. Mag.*, xxvi (1942), p. 197.

² Termed *mafurite* by Holmes.

latest constituents to crystallize, and forms intricate dendritic growths in the interstitial glass (Fig. 53). Further, magnetite is produced at different stages in the history of a rock by alteration of iron-bearing silicates. A familiar instance is the serpentinization of olivine; while the conversion of amphibole into pyroxene liberates magnetite (Fig. 53, A).

Probably the most striking magnetite-rich igneous rocks form part of the great Bushveld Complex in the Transvaal. They are associated with pure plagioclase rocks (anorthosites) and more normal basic rocks of the norite type, and vary from magnetite-anorthosite through types in which titano-magnetite steadily increases at the expense of the plagioclase until pure lodestone results.

Ilmenite.—Ideally ilmenite is titanite of iron, FeTiO_3 , but in

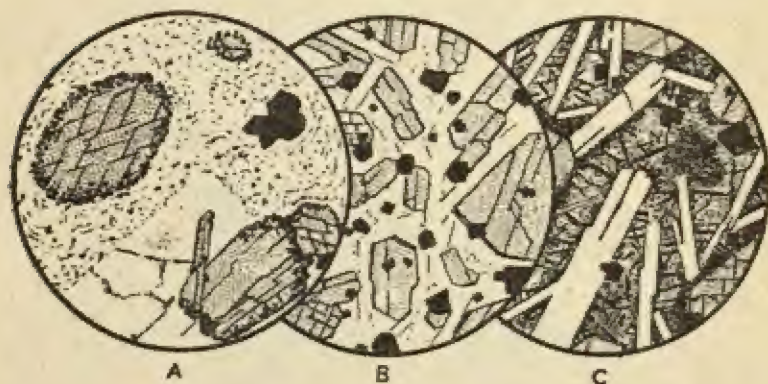


FIG. 53

Iron ores in thin section. (A) Magnetite grains produced round hornblende phenocrysts by magmatic corrosion, in hornblende-andesite, Siebengebirge (x32); (B) early crystallized, euhedral magnetite grains in dolerite (x32); (C) Early formed euhedral crystals, and very late iron ore embedded in glassy groundmass, in olivine-basalt, Hawaii (x60).

naturally occurring specimens some substitution of Ti by Fe has taken place, so that up to 30 per cent of Fe_2O_3 may be shown on analysis. Ilmenite crystallizes in the Trigonal System, but actual crystals are rare, and normally the mineral is massive. It is quite opaque, and is therefore sometimes difficult to distinguish from magnetite, especially when quite fresh. Alteration renders the task easier, however, for ilmenite is progressively converted into leucoxene. In an early stage, the change is superficial only, and the grains appear white by reflected light. In an advanced stage of alteration the mineral becomes translucent, light brownish-grey in

colour, while the Trigonal symmetry is emphasized by thin parallel black bars crossing in three directions (Fig. 54). At one time leucoxene was thought to be secondary sphene in the process of formation, but it has been shown¹ to be hydrated oxide of titanium, $\text{TiO}_2 \cdot n\text{H}_2\text{O}$.

Compared with magnetite, ilmenite is less variable in mode of occurrence. It normally occurs as an accessory mineral, particularly in the more basic, coarse-grained igneous rocks of the gabbro type. In such rocks, indeed, the ilmenite is an essential constituent, and occasionally increases in amount, particularly towards the base of

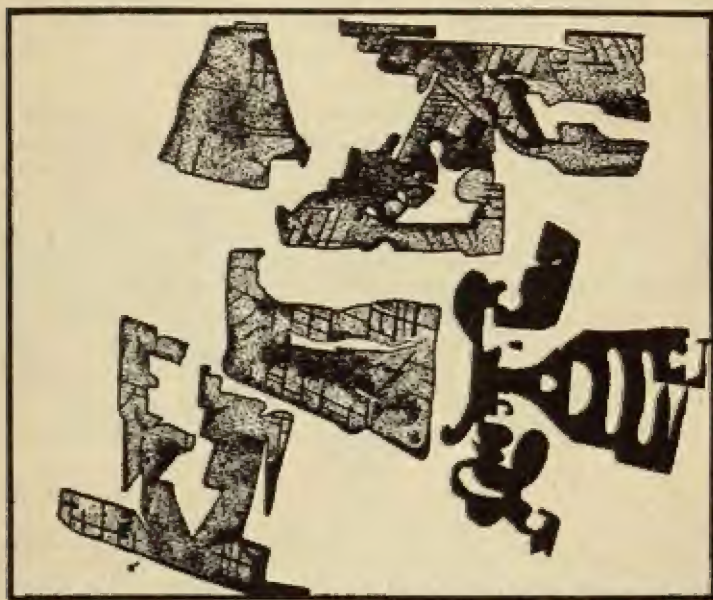


FIG. 54

Ilmenite and its alteration products; from lugarite, Lugar, Ayrshire. The one skeletal crystal is fresh; the others have been altered into grey-brown translucent leucoxene traversed by bars of iron-oxide.

stratified basic intrusions, and may become quantitatively an important constituent. In this country the Carrock Fell gabbro is a well-known illustration: some marginal facies of the gabbro contain up to 27 per cent of titaniferous iron-ore (and a correspondingly low silica percentage of 32).²

¹ Edwards, A. B., "The Chemical Composition of Leucoxene . . .," *Min. Mag.*, xxvi (1942), p. 273.

² Harker, A., *Natural History of Igneous Rocks*, 1909, p. 133.

Pyrite.—This iron-ore is the non-magnetic sulphide of iron, FeS_2 , which crystallizes in one of the lower symmetry classes of the Cubic System. The forms exhibited include the cube, octahedron, and perhaps most typically the pentagonal dodecahedron or pyritohedron (210). The crystallographic characters, light brassy colour and metallic lustre render pyrite distinctive.

In thin section it is opaque, but the distinction from magnetite and ilmenite should present no difficulty, for the metallic lustre and brassy appearance are diagnostic when the mineral is examined by reflected light.

It is doubtful if pyrite ever occurs as a primary constituent of igneous rocks, but it is common as a secondary mineral, associated with calcite, chlorite and secondary quartz, etc.

Pyrrhotite has the same chemical composition as pyrite, but crystallizes in the Hexagonal System. When quite fresh pyrrhotite resembles pyrite, though it is somewhat darker in colour. Exposure causes it to tarnish, and ultimately it assumes a characteristic bronzy appearance. A further point of difference between these two sulphides is that pyrrhotite is magnetic, though variably so. The mineral is uncommon in igneous rocks, but has been recorded from various nepheline-bearing rocks and, much more rarely, from acid igneous rocks.

Haematite.—This oxide of iron, Fe_2O_3 , provides many well-crystallized combinations of rhombohedra, scalenohedra and striated basal pinacoids in most mineral collections. Such specimens, however, are rarely obtained from igneous rocks, and then only as a product of fumarole action. Normally haematite fills a very different rôle in igneous rocks: it occurs finely disseminated in many different types, colouring them red. This pigmentary haematite appears in thin section as small bright red flecks or sometimes veinlets, it may be, emphasizing the cleavages of feldspars. Although well-crystallized specimens look like tempered steel, their powder and their streak show this characteristic rich red colour.

Limonite.—There are several hydrated oxides of iron, of which, for present purposes, limonite and goethite are the most important. The latter is Orthorhombic, while the former is amorphous; otherwise the two minerals have much in common, and there is no doubt that much of the mineral called limonite in igneous rocks is really goethite. Both are typically brownish in the mass, and yellow to yellowish-brown in thin section. Obviously there are significant optical differences consistent with the crystallographic differences. Thus goethite is pleochroic and birefringent; while amorphous limonite can exhibit neither phenomenon. It is possible that limonite is merely cryptocrystalline goethite, but on the other hand, while

the former may be represented by the formula $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$, the latter is $\text{FeO}(\text{OH})$, which may be written $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$.

"Limonite" is always secondary in igneous rocks and is liable to be produced, within the zone of weathering, from any iron-bearing silicate, or other iron-ore mineral.

(e) APATITE

Apatites are essentially phosphates of calcium, with a small amount of fluorine, chlorine, and/or hydroxyl. According to the dominance of either fluorine or chlorine, two varieties, fluor-apatite and chlor-apatite are distinguished: the former is much the commoner in rocks. Apatite crystallizes in the Hexagonal System, in the class in which there are no vertical planes of symmetry; but usually the crystal development is so simple—a combination of prism in zone with a bipyramid and basal pinacoid—that this would pass unnoticed, were it not for the occasional occurrence of the general form.¹ Cleavage parallel to the base is imperfect, but characteristic in thin sections. Apatite may be colourless, but is often bluish in hand-specimens, though almost invariably colourless in thin section.

Apatite is a ubiquitous accessory in igneous rocks of all kinds, and seems to be particularly abundant in those of basic composition. Indeed, its characteristic colourless elongated rectangular vertical sections, and small perfect hexagonal basal sections are more widely distributed than any other accessory mineral. The prisms in some instances may be acicular. The relief is moderate, with $\alpha = 1.630$ and $\gamma = 1.632$ (minimum values), with a weak birefringence (0.002). In "cored apatites" there is a central coloured zone.

In some nepheline-syenite complexes apatite occurs in important amounts, and from the Kola Peninsula in the U.S.S.R., a rock occurs which consists solely of apatite and sphene.

(f) BERYL

Beryl, a silicate of beryllium and aluminium, has an interesting atomic structure, the essential unit of which is a ring of six SiO_4 tetrahedra. As each tetrahedron shares two of its four oxygen atoms with its neighbours in the ring, the formula of the unit may be written Si_6O_{12} . To restore the balance between the positive and negative charges on this unit, three Be and two Al atoms are required, giving the complete formula $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$. The Be and Al atoms, of course, link the rings together.

Beryl crystallizes in the Hexagonal System, and exhibits holosymmetry—the full complement of one horizontal and six vertical

¹ Phillips, F. C., *An Introduction to Crystallography*, 1946, p. 136.

planes, six diad axes and a vertical hexad axis. Apart from its higher symmetry, beryl may resemble apatite, but has a totally different mode of occurrence, and fills a very different rôle. Small beryls occur in euhedral crystals in cavities in granite of the Mourne Mountains and Lundy Island, for example; but much larger crystals, some of phenomenal size, occur in granitic pegmatites (p. 204). The brilliant green gemstone, emerald, is a species of beryl, but is of metamorphic origin.

(g) THE ZIRCONIUM-BEARING GROUP

Zircon, a silicate of zirconium, ZrSiO_4 , is one of the best-known minerals which crystallize in the Tetragonal System. The crystals consist of bipyramids in combination with prisms, sometimes the one, sometimes the other being dominant. Again, the bipyramid faces may be in zone with the prism, or may be of a different order (Fig. 55).

The crystals are commonly light brown, buff or reddish-brown,

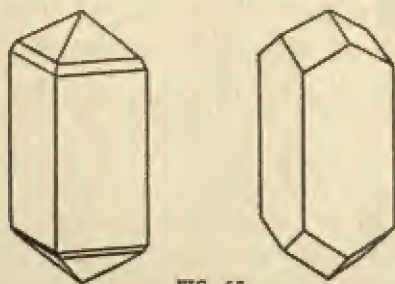


FIG. 55

Crystals of zircon.

Left, vertical prism (110) combined with Tetragonal bipyramids (111) and (331);
Right, prism (100) with bipyramid (111).

while phenocrystic zircons of bright red colour, with subvitreous lustre, occur in a grey slaggy lava from Niedermendig, Germany.

In rock sections zircons are common in granitic, syenitic and dioritic rocks, but appear to be rarer in those of more basic composition. As a general rule they are of small (microscopic) size, colourless with high refractive indices ($\alpha = 1.927$, $\gamma = 1.982$). The birefringence is likewise strong (0.055). As they crystallize at a high temperature, they are liable to be enclosed in minerals of later formation, and are most obvious when embedded in biotite, when they are surrounded by pleochroic haloes caused by the bombardment of the host-mineral by alpha-particles emanating from the zircon.

In certain types of nepheline-syenites the zircons are of much

larger size and have the status of an essential constituent, particularly in the coarse-grained "zircon-syenite-pegmatites."

Eudialyte is one of a number of complex zircono-silicates which occur as accessory minerals in nepheline-syenites, particularly of pegmatitic facies. It increases in amount in more basic nepheline-bearing rocks and may attain to the status of an important essential constituent, as in the so-called eudialyte-syenites in southern Greenland. One rock near Julianehaab, in this area, contains eudialyte to the extent of a third of the whole rock. It is also important in similar rocks in the Kola Peninsula, U.S.S.R. In Britain it has been recorded, for the first time, from quartz-syenite veins in limestone at Barnavave, Ireland.¹

Eudialyte is a Trigonal mineral, is commonly bright red in the hand specimen, and therefore very distinctive in appearance. In thin section it is often colourless, but may be pink, and then exhibits a pink to yellow pleochroism. Refrindex is moderate, with $\alpha = 1.609$ and $\gamma = 1.611$. The birefringence is notably weak—about 0.002.

ACCESSORY MINERALS: THE "PNEUMATOLYTIC GROUP"

(a) **Tourmaline Group.**—Tourmalines are complex hydrated silicates and borates of aluminium, magnesium and sodium, with iron, manganese, calcium and small quantities of potassium, lithium and fluorine. The tourmalines may, according to their constituent bases, be classified as alkali-tourmalines, iron-tourmalines, magnesium-tourmalines, etc. They all contain about 10 per cent of boric acid, and from $3\frac{1}{2}$ to 4 per cent of water. Tourmaline crystals are Trigonal, occurring in triangular prisms with pyramidal terminations, sometimes accompanied by a basal plane or pedion.

From many points of view, tourmaline is a mineral of outstanding interest. Crystallographically it provides striking examples of polar symmetry, the terminations of some specimens being obviously different; while if the crystals are so simple as to show a single horizontal plane at both ends, the complete independence of these pedions is proved by physical differences between them, one being as lustrous as glass, while the other may be lustreless or strongly etched. This polar symmetry is in many instances shown by an unsymmetrical distribution of colour along the length of the crystal: this is most spectacular in certain parti-coloured crystals of gemstone quality, which are coloured rich pink at one end and bright green at the other.

¹ Nockolds, S. R., *Min. Mag.*, xxix (1950), p. 27.

Characteristically the prism zone is strongly striated due to oscillation between the dominant trigonal prism and the hexagonal prism which modifies its edges (Fig. 56).

In *thin section* tourmaline may occasionally be colourless; but normally it is blue, brown or green, and strongly pleochroic. The absorption of the ordinary ray is much stronger than the extraordinary, so that prismatic sections show their deepest colour when

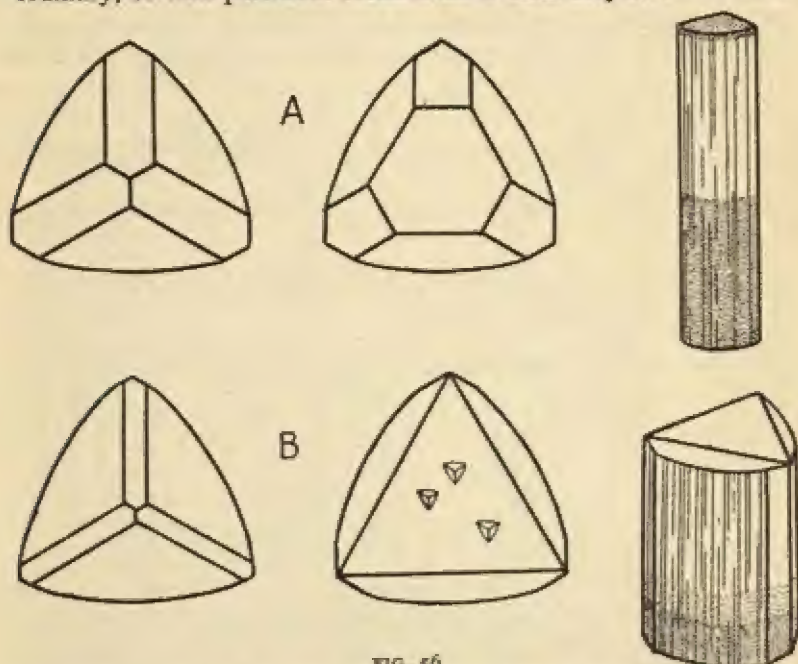


FIG. 56

Tourmaline crystals. (A) The two differing terminations of one crystal, showing combinations of positive and negative trigonal pyramids at one end, and similar forms with the addition of a pedion {0001} at the other. (B) Similar combinations shown by a crystal of slightly different habit, with the characteristic shape of etched figures added diagrammatically. The crystals (right) show polar colour variation and vertical striations. Tourmalines of gem quality from Minas Geraes, Brazil.

the principal axis lies perpendicular to the vibration direction of the polarizer in the microscope.¹

Basal sections, often of modified triangular cross section, are frequently zoned, even if the crystal is minutely acicular. They yield a negative uniaxial interference figure in convergent light. The birefringence of tourmaline varies with composition, reaching a

¹ The vibration of the polarizer lies parallel to the cleavage traces in a vertical section of biotite, when the stage has been turned to the position in which the mineral shows its deepest absorption tint.

maximum of 0.046 in varieties rich in chromium, but averaging 0.029 in "schorl"—the type commonly occurring in tourmaline-granites and associated rocks.

Tourmaline is essentially a component of the so-called pneumatolytic rocks and of granite-pegmatites. Thus it is widely distributed in and around the West of England granites. In part it is a primary mineral, but in large measure it has been produced at the expense of pre-existing mica and feldspar, in which case it commonly assumes a distinctive habit, much-elongated acicular crystals with a radial

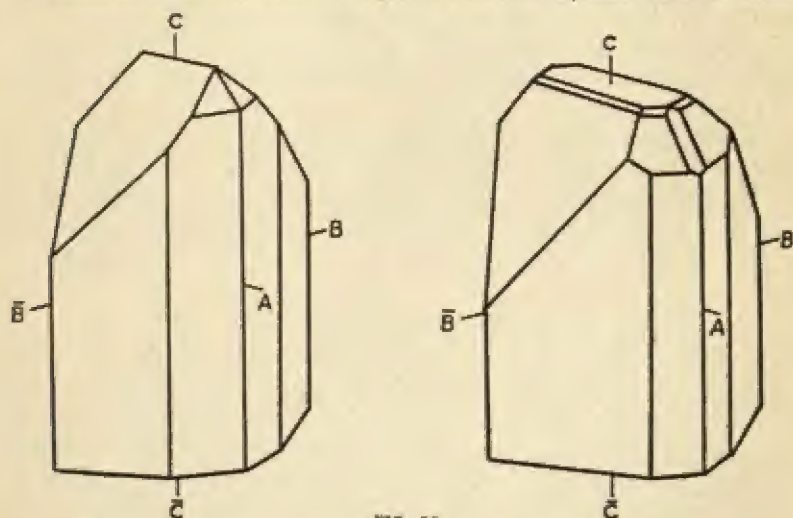


FIG. 57

Crystal habits of topaz from Kleine Spitzkop, South-West Africa. Combinations of vertical prisms {110} and {210}; the dominant "dome" {021}, the "dome" {101} and bipyramids. The crystals are single ended, being bounded below by basal cleavage planes.

disposition, or being so closely packed as to form a felt-like aggregate (see under "Pneumatolysis," p. 208 and Fig. 86).

(b) **Topaz** is the fluosilicate of aluminium, $\text{Al}_2(\text{F}, \text{OH})_2\text{SiO}_4$, which crystallizes in the Orthorhombic System. The crystals are of prismatic habit, the faces in the zone parallel to the principal axis being strongly striated vertically, due to oscillation between the unit prism and another in zone with it. The terminations may be very complex, with a development of domes, bipyramids and basal pinacoid. Usually the end of the crystal is dominated by the dome {021}, (Fig. 57).

Topaz of gemstone quality from certain well-known localities in Brazil has a distinctive honey-brown colour; other varieties may be faintly tinted blue, but many are quite colourless. The basal cleavage is perfect but difficult to produce artificially.

Optically topaz is characterized by moderate refractive indices, 1.615 for α and 1.625 for γ . Thus the birefringence, 0.009, is almost identical with that of quartz, though the relief is considerably stronger. Naturally the mineral is biaxial; it is of positive sign, with the acute bisectrix emerging perpendicular to the basal cleavage. Thus an observation in convergent light will usually confirm the diagnosis.

Topaz occurs in irregular grains and spongy masses in pneumatolytic rocks, notably in greisens. In such rocks the amount of topaz may be very large: in a "topazfels" from Schneckenstein in Saxony, 80 per cent of the rock is topaz. The mineral also occurs rarely as a primary mineral in granites, though it appears to be restricted to the irregular druses in the Mourne Mountains and Lundy Island granites. The large crystals of gemstone quality are obtained from pegmatites.

(c) **Fluorite** (popularly termed fluorspar).

Fluorite is the fluoride of calcium which crystallizes in the holosymmetric class of the Cubic system. Normally the cube, as simple crystals or interpenetrant twins, is the only form seen; but occasionally the cubes may be modified on the edges by the tetrahexahedron (210) or on the corners by the octahedron (111). Fluorite may be quite colourless, but is commonly tinted green, blue, or typically violet. A most distinctive feature is the brilliant fluorescence in vivid, luminous blue, when illuminated with ultraviolet light.

In *thin section* fluorite shows very strong negative surface relief (on account of its abnormally low refractive index, 1.434), and traces of a highly perfect octahedral cleavage (Fig. 87). The sections are perfectly isotropic. Normally they are colourless but occasionally the characteristic violet colour appears, even in a section of normal thickness.

Fluorite occurs in the so-called pneumatolytic rocks and is especially characteristic of greisens, where it is associated with topaz, another fluorine-bearing mineral. It is also a common gangue mineral, for example, in the lead-mining area of the northern Pennines, whence come so many of the beautifully crystallized specimens that grace mineral-cabinets.

ACCESSORY MINERALS: PRODUCTS OF CONTAMINATION

(a) **Corundum.**

There are three very distinct varieties of this mineral—common corundum, and the clear gem-stones, ruby and sapphire. These all crystallize in the rhombohedral class of the Trigonal System, but the crystal habit is very variable; the crystals are combina-

tions of hexagonal prism, bipyramid and basal pinacoid, with the rhombohedron, the presence of which establishes the symmetry class to which the mineral belongs, and in addition determines the directions of the characteristic surface markings on some of the crystal faces (Fig. 58, C). Oscillation between the prism and the bipyramid causes strongly developed horizontal striations (Fig. 58, B). It is probably more than a coincidence that true sapphires are frequently of bipyramidal habit (the clear blue crystal shown in Fig. 58, A is a case in point); while rubies of gemstone quality are often rhombohedral. Common corundums may be tabular, bipyramidal with very irregular faces (Fig. 58, B) or prismatic (Fig. 58, C).



FIG. 58

Three crystal habits of corundum

- (A) Sapphire: combination of hexagonal prism and bipyramid;
 (B) Opaque red corundum, Ceylon: combination of heavily striated bipyramid, rhombohedron and basal pinacoid.
 (C) Common corundum, Pietersburg, Transvaal, South Africa: combination of hexagonal prism, rhombohedron and basal pinacoid, with characteristic surface markings.

In composition all varieties are essentially alike, only differing in the minute amounts of trace elements that act as pigments to the coloured varieties. Apart from these, corundum is just crystallized alumina, Al_2O_3 .

Corundum is notable for its extreme hardness (9 in Moh's scale). It has a parting parallel to the *ooor* face. Optically corundum is distinguished by its high refractive indices ($\alpha = 1.760$, $\gamma = 1.768$) and weak birefringence (0.008), almost the same as quartz. Normally corundum is colourless in thin section, but a strongly coloured sapphire is light blue, and of course slightly pleochroic. In convergent light a uniaxial negative interference figure confirms the identification.

Although corundum is typically a product of the thermal metamorphism of argillaceous sediments, it does originate in other ways,

and is a rare constituent of some types of igneous rocks. In the form of small blue sapphires, corundum has been described from argillaceous xenoliths in basic intrusions of Tertiary age in Mull and Ardnamurchan. In a totally different manner potential corundum is liberated by the thermal metamorphism of sericitic mica; but normally the latter is accompanied by quartz, with which the potential corundum combines to form actual andalusite. Naturally, corundum can occur only in quartz-free igneous rocks, and it appears to be restricted to those rocks which have suffered desilication: that is, they have contributed silica to the adjacent wall-rock. Thus certain syenitic and dioritic rocks from the Bancroft area in Ontario and from some South African localities, are corundum-bearing. Finally, a basic intrusive occurring as a dyke at a locality in Pennsylvania is near anorthosite (a basic plagioclase rock) in composition; but in a crush zone the plagioclase has been converted into the barium feldspar, hyalophane, and the latter is charged with small corundum crystals representing the surplus alumina resulting from the conversion.

(b) The Aluminium-Silicate Group.

(i) **Andalusite.**—This mineral is one of a number of silicates of aluminium and may be represented by the formula Al_2SiO_5 , being thus identical in composition with sillimanite (which may be regarded as the high-temperature equivalent of andalusite), and kyanite, its stress equivalent. Andalusite is an Orthorhombic mineral, but it exhibits strong pseudo-tetragonal symmetry, and unless the crystals are terminated, they might easily pass for Tetragonal prisms (Fig. 59). In appearance the crystals are rather undistinguished: they are usually grey, with resinous lustre, and a surface coating of white mica into which the mineral readily alters.

In thin section andalusite may be distinctive, largely by reason of its pleochroism. At its best the colour corresponding to the slow vibration, Z, is the pink of peach blossom, while X and Y may be both colourless, or there may be a trace of bluish-green. This pleochroism scheme is, in fact, closely similar to that of hypersthene. In many rocks, however, the andalusite is non-pleochroic. The refractive indices are moderate, with $\alpha = 1.635$ and $\gamma = 1.643$ (average values); while the birefringence is weak, varying in different specimens from a little below, to a little above quartz. Traces of prismatic cleavage, in basal sections crossing at almost a right angle, are consistently developed, but the sections are strongly sieved with small inclusions of the associated minerals, which sometimes render systematic examination rather difficult.

Typically andalusite occurs in argillaceous hornfelses, in which it

is accompanied by cordierite, biotite and often spinel, and is one of the first newly crystalline minerals to appear in these rocks.

It also occurs somewhat rarely as an accessory in igneous rocks, and must then be regarded as evidence of the assimilation of argillaceous xenoliths.

(ii) **Chiastolite** is merely a variety of andalusite containing regularly arranged carbonaceous inclusions (Fig. 59). It occurs in

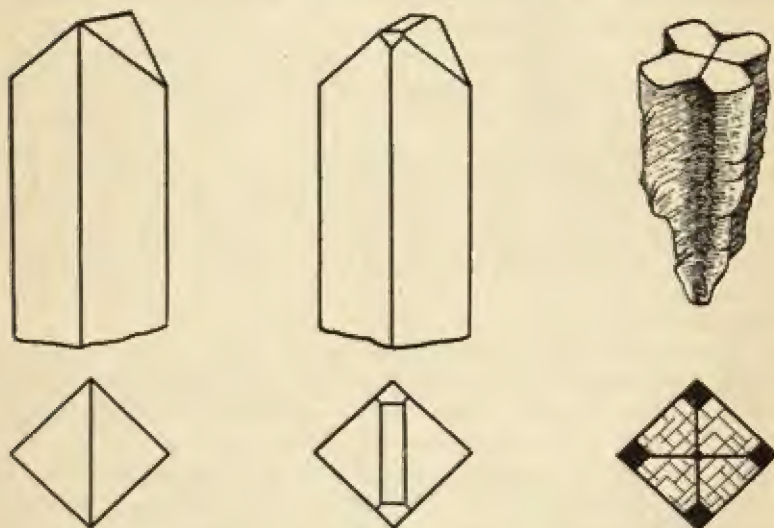


FIG. 59

Andalusite and chiastolite crystals.

Left: Combination of prism (110) and "dome" (011). *Centre:* A more complicated crystal showing the forms (001) and (101) in addition. *Right:* A weathered crystal of chiastolite; below, the ideal cross-section showing prismatic cleavages and characteristic carbonaceous inclusions.

the so-called chiastolite-slate which occurs within the aureole of thermal metamorphism round granites. Well-known British examples occur near the contact between the Skiddaw granite and the Skiddaw slates.

(iii) **Sillimanite**, as stated above, is a high-temperature equivalent of andalusite. Both of these minerals dissociate at about 1545° C into mullite and liquid, while at 1810° C corundum and liquid are produced. In most cases sillimanite occurs as aggregates of thin prisms, acicular crystals, or finely fibrous aggregates (fibrolite). They are colourless in thin section, with moderate relief and moderately strong birefringence. Sillimanite cannot be regarded as a normal constituent of igneous rocks; but it may arise in the

manner described above for andalusite—by the assimilation at high temperature of argillaceous xenoliths.

(iv) **Mullite** was discovered during the examination of the system $\text{Al}_2\text{O}_3\text{--SiO}_2$ in the Geophysical Laboratory at Washington,¹ and was so named after a natural occurrence in Mull, Scotland. It appears to be rare in igneous rocks, but under laboratory conditions crystallizes from melts having the composition of sillimanite and is a well-known constituent of porcelains. The composition is represented by $\text{Al}_6\text{Si}_2\text{O}_{13}$, which may be expressed as $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$. Mullite remains rather a problem mineral: it has been claimed to be merely an intimate admixture of sillimanite and corundum in equal molecular proportions,² but "boules," each consisting of a single large crystal of mullite have been made, using a flame-fusion technique. In these, X-ray examination proves there to be *no* corundum. The original mullite, from Mull, occurs in argillaceous xenoliths embedded in Tertiary basaltic dykes.

(v) **Kyanite** is the Triclinic form of Al_2SiO_5 . In occurrence it is almost restricted to the crystalline schists, and thus appears to be the form that is stable under stress conditions.

Coarsely crystalline kyanite is easy to identify in hand specimen, since the crystals are very much elongated parallel to the c-axis, and have a characteristic pale sky-blue colour, although sometimes they are whitish and have a pearly lustre. The crystals may be slightly bent, and are always well cleaved. The most perfect cleavage is parallel to the front pinacoid (100), which is always a prominent face in the slightly flattened tabular crystals. The (010) cleavage is rather less perfect, and in addition to these there is a more widely spaced basal parting.

In thin section, kyanite is colourless, and characterized by a high surface relief and first order grey to yellow interference colours: the refractive indices are $\alpha = 1.715$ and $\gamma = 1.728$, with a birefringence of 0.013. The determination of kyanite can be confirmed by means of the optical orientation. The most useful section for this purpose is that parallel to (100), which has a sensibly rectangular cleavage pattern. The slow vibration direction Z, makes an angle of 30° to the length of the crystal and also to the (010) cleavage; while X, which is the acute bisectrix, emerges perpendicular to the section.

In metamorphic schists, kyanite is often associated with staurolite, and sometimes in intimate intergrowths with the latter. It is also found as an accessory mineral in some eclogites.

¹ Bowen, N. L., Greig, J. W. and Zies, E. G., *Journ. Wash. Acad. Sci.*, xiv (1924), p. 183.

² Eitel, W., *Zeit. Kryst.*, lxiv (1927), p. 536.

(c) **Cordierite.**

This silicate of aluminium, magnesium and iron occurs in a wide variety of rocks of different kinds. It is often a challenge to the skill of the petrographer on account of lack of distinctiveness in its optical characters. The composition may be represented by the formula $Mg_2Al_4Si_2O_{18}$; but this may be written in a form reminiscent of beryl, except that the Si_2O_6 of the latter becomes $(AlSi_2)_2O_6$ —a proxy-Al replacing a Si atom—in cordierite. This is significant, for although cordierite is an Orthorhombic mineral, it is strongly pseudo-hexagonal, particularly when twinned. Natural crystals are prismatic in habit, but are relatively rare. When fresh, cordierite is violet in colour and pleochroic, the obsolete name "dichroite" having been applied to it on account of its strong pleochroism. There is no true cleavage, but a basal parting is characteristic.¹

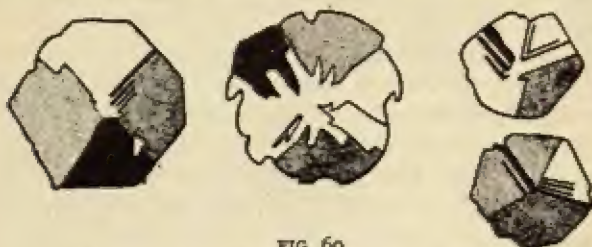


FIG. 60

Sections of cordierite between crossed nicols,
showing sectorial twinning.
From cordierite-norite, Arnage, Banffshire.

The optical properties vary with the content of iron; but commonly the sections are quite colourless in thin slice, while the indices are low— $\alpha = 1.535$, $\gamma = 1.544$. Thus one index is the same as quartz and the surface relief is the same as that of the latter mineral, so is the birefringence (0.009); and it is therefore often very difficult to distinguish between the two minerals. Under the most favourable conditions the twinning is diagnostic. Ideally the twins comprise three or six sectors; but actually the number of sectors varies (Fig. 60), and it may be complicated by lamellar twinning superimposed on the sectorial. As the twin planes are prism faces, vertical sections are similar to simple twins of feldspar, while the lamellar twinning may cause an uncomfortably close resemblance to plagioclase. However, cordierite is characteristically closely associated with spinel, often in swarms of small dark green octahedra; and yellow pleochoric haloes occur round minute inclusions of zircon and rarer

¹ Cf. Winchell, N. H. and A. N., *Elements of Optical Mineralogy*, 1927, p. 273. These writers record three, pinacoidal cleavages, the best parallel to 010.

accessories. Finally, the crystals may show any degree of alteration to an aggregate of white mica and chlorite, termed "pinite." Obviously as the mineral is Orthorhombic it must be biaxial—a fact readily checked in a basal section, to which the acute bisectrix, *X*, is perpendicular.

As regards mode of occurrence, cordierite is typically a product of thermal metamorphism of argillaceous sediments—it is commonest in hornfelses and is accompanied therein by such minerals as andalusite, biotite, spinel and corundum. It occurs, also, though much less commonly, in basic and in acid igneous rocks, in which it undoubtedly represents imperfectly digested xenoliths of argillaceous material. The cordierite-garnet-norites of Aberdeenshire provide good examples.¹ The Land's End granite contains euhedral greenish-grey pinitic pseudomorphs after cordierite, up to an inch or so in length. More rarely the mineral is found—again usually in xenoliths—in lavas such as basalt and andesite. Cordierite crystals or aggregates, often of large size, occur also in pegmatites in several localities. As the mineral is not usually present in the wall-rock, which in different instances is igneous (either acid or basic) or metamorphic, it is inferred that the cordierite has been formed from the pegmatitic liquid, *not* from caught-up (xenolithic) material.

¹ Read, H. H., "The Geology of Banff, Huntly and Turriff," *Mem. Geol. Surv.*, 1923, pp. 128-137.



PART II

MODE OF INTRUSION AND CONSOLIDATION OF MAGMA



MODE OF OCCURRENCE OF THE EXTRUSIVE ROCKS

IGNEOUS rock-masses may be very simply divided into two major categories, viz.: (i) those that crystallize within the crust; and (ii) those that solidify at the surface. The former are commonly called "intrusions," the latter extrusions, or lava flows.

Since lava flows are the only igneous rock-bodies which can be actually observed in the process of formation, they form the logical starting-point for the study of igneous rocks. They demonstrably result from the consolidation of extremely hot fluid magma erupted at the surface. Only in so far as the intrusive rocks are analogous in composition and texture to the lavas, can a common magmatic origin be legitimately inferred. No question arises as to the origin of most of the sheet-like intrusions (dykes and sills); they evidently represent material identical with that of the lava flows, but injected into crustal fissures. The field relations of certain "igneous" veins suggest a replacive, rather than a displacive origin, however. There remain the coarsely crystalline silicate rocks, often of great surface area, and unknown—and unknowable—extension in depth. These are commonly classified as "major intrusions"; but in the present state of knowledge it is preferable to use a non-committal term with no implications as to origin, such as "pluton."

Lava Flows.

Lava is molten rock material—magma—poured out through a vent or fissure. The flow may be subaerial or submarine. In subaerial flows the lava forms streams of greater or less extent, according to the fluidity of the magma, the more basic being the more fluid. Thus, some of the Icelandic lavas of basaltic composition were so fluid that they extended for forty to fifty miles from the point of eruption.

With submarine flows the lava is spread over, and succeeded by, normal sediment: it forms part of the stratigraphical succession and is said to be *contemporaneous*. The date of the outpouring can obviously be fixed by means of the fossils contained in the contiguous strata. Thus lavas erupted at intervals during the Carboniferous Period cover considerable areas in the Midland Valley of Scotland. Basaltic outpourings on the grandest scale occupy vast areas in

Idaho, Oregon and Washington, in the Parana Basin in Brazil and in the Deccan, India, where the lavas known as the Deccan Traps cover an area of some 200,000 square miles. These vast basaltic plateaux appear to have been built up by numbers of flows, individually of no great thickness, erupted through fissures, and therefore fed by dykes. This form of extrusion, known as **fissure-eruption**, has taken place within historical times in Iceland. On account of the relative absence of explosive volcanic activity, fissure-eruptions are believed to take place with a quiet outwelling of the lava.

Contrasting with these fissure-eruptions are those of **central type**. In these, the energy concerned in producing the uprise of the magma, instead of being dispersed over wide areas, is localized at certain points, where the familiar craters are established. The actual form of the volcano is determined by the type of magma, which is more variable in composition than in the plateau-lavas of fissure eruptions. Where the magma is basaltic, widespread lava-domes of the type magnificently exemplified by the Hawaiian volcanoes, are built up. This volcanic pile, covering an area of well over a hundred miles in horizontal extent at the base, rises from the floor of the Pacific to a height of 13,000 ft. above sea level. Contrasted with these lava-domes are the very much smaller, steep-sided cones, built largely of exploded volcanic debris, loosely known as volcanic ash, lying at the angle of rest, and to some extent reinforced by veins of intrusive rock. The well-known Etna and Vesuvius are volcanoes of this type.

The acid (trachytic) lavas of Auvergne in France were erupted in such a viscous condition as to form hummocky or dome-shaped masses of small lateral extent. These are the familiar "puys" of Auvergne. A special development of the latter type is illustrated by the disastrous eruption of Mont Pelée in Martinique, when, following the formation of an incandescent "cloud" (*nuée ardente*) of finely divided ash, a massive "spine" or column of andesitic lava was slowly protruded, and reached a height of 800 ft. above the crater.

Volcanic Necks.—A volcano of the central type is connected to the underground source of magma by a pipe of roughly circular cross-section. With the cessation of activity this "neck" survives long after all trace of the actual crater and of the lavas erupted from it have disappeared as a consequence of denudation. The material which fills the neck is of two kinds: firstly, it may be lava which congealed before reaching the crater; or it may be fragmental material formed by explosions during the period of activity. The former is covered by the term "*vent intrusion*," and the latter is said to be *pyroclastic*, and may range from accumulations of great angular blocks to finely pulverized rock—the so-called volcanic

ash. These pyroclastic materials are considered more fully in a later section. The vent-intrusions are usually lithologically and texturally indistinguishable from surface lava flows.

In this country parts of the Midland Valley of Scotland are noteworthy by reason of the large numbers of small volcanic necks

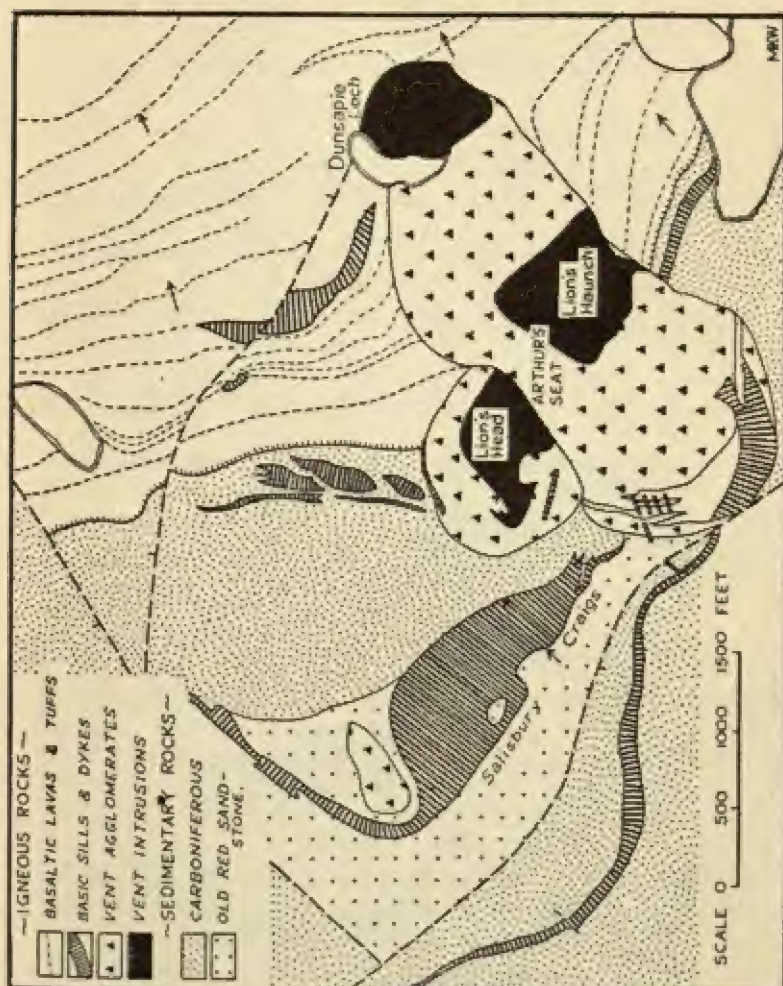


FIG. 61

Simplified map of the Carboniferous lava flows, intrusions and volcanic vents in the vicinity of Edinburgh.

(After H.M. Geol. Survey)

which have been located, especially in Fifeshire and Ayrshire. In the former locality many of the vents are seen in cross-section on the coast. An outstanding example, occurring on the outskirts of Edinburgh, forms Arthur's Seat, a very prominent landmark over a wide stretch of country (Fig. 61).



FIG. 62

Cross-section of the Arthur's Seat vents. The key to the ornament is given in Fig. 61.

The Structure of Lavas.

From direct observation it is possible to distinguish a number of types of lava-flow. Under subaerial conditions the flow may resemble a tumbled mass of clinker or slag. This is distinguished as **block-lava**, and results when the volatiles in the magma are boiled off in the vent, before eruption. With more rapid uprise and less loss of volatiles the solidified lava shows on the surface contorted, snaky folds, suggestive of irregular viscous flow. This is **ropy lava**. A feature highly characteristic of submarine lavas of all ages is **pillow structure**. Lavas exhibiting this structure consist of isolated

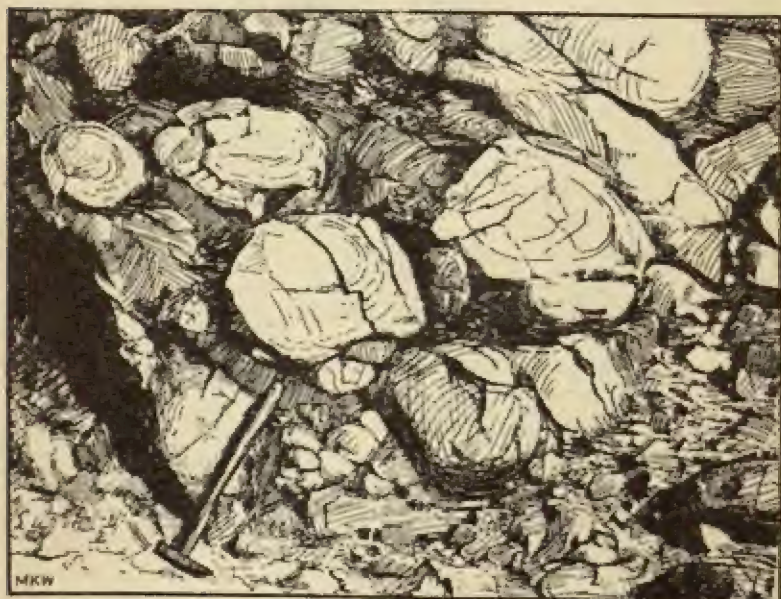


FIG. 63

Pillow lavas (spilites) with jasper between some of the pillow structures, Anglesey.

(M.K.W. after photo by H.M. Geol. Survey.)

pillow-shaped masses piled one upon another, the intervening spaces being filled with sedimentary material, sometimes chert, sometimes limestone, sometimes hardened shale (Fig. 63). Internally the pillows are characterized by concentrically arranged vesicles, and occasionally there is a central ovoid cavity. Pillow structure is shown by basaltic and andesitic lavas, while the most perfect examples occur in flows of spilite, a type of albite-basalt. In the case of the spilites, instead of parting at once with the steam incorporated in the lava, when erupted on the sea-floor, the pillows swelled up like a sponge and retained sufficient steam in the vesicles to drastically reduce the density. Moreover, such lavas on eruption seem to have been in the spheroidal state, and since each spheroid or pillow as it became detached was jacketed in steam, the lava flowing over the sea-floor formed a mobile sheet of rolling spheres, seldom touching one another until they had cooled down. Subaerial lavas cannot show typical pillow structure. In Britain the best examples of pillow-lavas are of Precambrian and Ordovician age, and are described in the final section of this book.¹

As a direct consequence of the conditions of outpouring, certain lavas are distinguished by marked flow- (or fluxion-) structure, due to the rolling over and pulling out of the semi-solid mass. This may result in very distinctive internal structures described in a later chapter. Certain lavas are characterized by a cellular or scoriaceous structure due to the elimination of water vapour and other gases during eruption.

If the gases are not boiled off during the uprise of the magma but are retained within it during solidification, a vesicular structure may result, provided that the vapour pressure within the vesicle exceeds the external pressure exerted upon it. The vesicles may remain spherical; but often as a result of flow movements within the lava they may be elongated. The presence of such ovoid vesicles, of extra large size, gives the lava amygdular structure. Both vesicles and amygdules (or amygdales) are subsequently filled with such minerals as calcite, chlorite, chalcedony and zeolites, presumably resulting from interaction between the imprisoned gases, chiefly water vapour, and the surrounding rock-forming minerals (Fig. 64).

Pipe amygdules have been described from lavas in many parts of the world. They commonly occur at the base of the flow, and have the form of long narrow cones, tapering upwards, up to a foot in length, and perhaps half-an-inch in diameter. They are filled with

¹ Wells, A. K., *Geol. Mag.*, lx (1923), p. 63 with references there quoted; also Reid and Dewey, "On the Origin of Pillow-Lava in Cornwall," *Quar. Journ. Geol. Soc.*, lxiv (1908), p. 264.

the same kinds of minerals as occur in the more normal ovoid amygdules. They appear to have resulted from the uprise of steam from the moist surface over which the lava flowed, for they commonly occur where lava was erupted over wet mud.¹

As a consequence of contraction due to cooling many igneous rocks come to be traversed by regularly arranged systems of intersecting joints. In its most perfect development—in certain basic lavas and minor intrusions—the resulting structure is aptly termed **columnar structure**. The columns, which are very often long and regular, are bounded by three, four, five or six planes,



FIG. 64

Vesicular basalt, Butaure, Tyrol.

producing triangular, quadrangular, pentagonal, and hexagonal prisms. Where the rock-texture is homogeneous the six-sided prisms are most prevalent, for of all the cases in which the centres of contraction are equidistant, and the angles of the prisms fit together without any intervening space, the hexagonal arrangement gives the highest ratio of area to periphery. The long axes of the columns are perpendicular to the retreating isotherms during cooling. In accordance with this law, the columns are vertical in horizontal sills and flows; while in dykes they are horizontal if the walls are vertical. In many lavas, particularly those of basic composition, three roughly parallel layers may be distinguished: an upper slaggy and vesicular portion; a central zone with somewhat irregular columns

¹ Du Toit, A. L., "Pipe Amygdaloids," *Geol. Mag.*, 1907, p. 13; Geikie, A., "Ancient Volcanoes of Great Britain," 1897, p. 17; Bailey, E. B., in "Geology of Knapdale, etc.," *Mem. Geol. Surv.*, 1911, p. 69.

of small cross-section, and a basal layer, with more massive, regular, hexagonal columns. These latter have grown upwards from the slowly cooling base; while the thin "wavy" columns grew downwards from the more rapidly cooling upper surface.¹ Fine examples of columnar jointing are found in the basic rocks of the Western

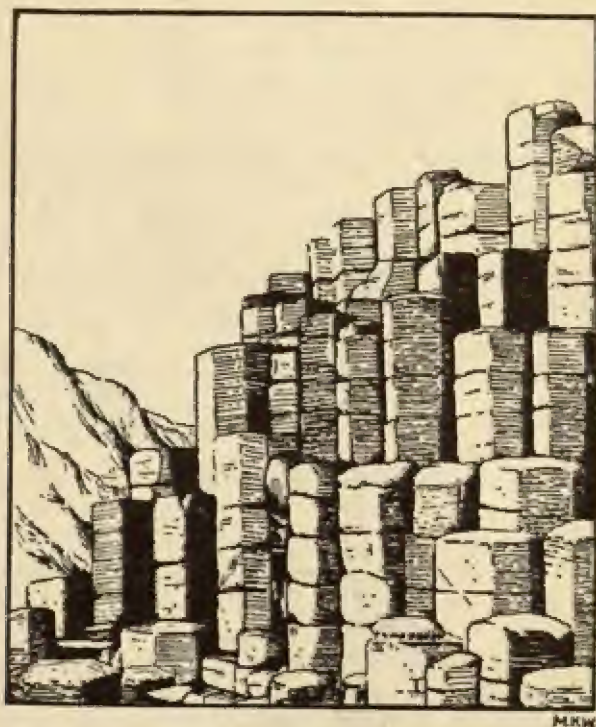


FIG. 65

Columnar basalt, Giant's Causeway, Co. Antrim, Ireland.

Isles of Scotland, as at Staffa and in Skye, also at Elie and St. Andrews in Fifeshire. Occasionally the columns are subdivided into segments by a subsidiary cross-jointing, and usually such segmentation is accompanied by a spheroidal tendency, producing *ball-and-socket joints*. Spectacular examples are seen at the Giant's Causeway in Antrim, by far the finest columnar basalt in Britain² (Fig. 65).

¹ "Tertiary and Post-Tertiary Rocks of Mull," *Mem. Geol. Surv.*, 1924, p. 109.

² Tomkeieff, S. I., "The Basaltic Lavas of the Giant's Causeway District of Northern Ireland," *Bull. Volc., Naples, Série ii, tome vi* (1940), p. 89.

MODE OF OCCURRENCE OF THE INTRUSIVE
ROCKS

SHEET-INTRUSIONS

(a) **Dykes.**—In this category we include all intrusions of sheet-like form which are vertical or nearly so, at the time of intrusion. Dykes vary in thickness from a fraction of an inch to hundreds of feet, but the average width is probably between one and three feet.¹ As a consequence of their attitude the outcrops of dykes are not affected by the topography of the country in which they occur: they therefore appear as nearly straight lines on geological maps, maintaining a uniform direction, sometimes for long distances. Parallel suites of dykes or dyke-swarms were intruded when a portion of the earth's crust was subjected to tension. The Lorne dyke-swarm in south-west Scotland, with a characteristic north-east to south-west trend, and the Mull dyke-swarm are typical examples (see Figs. 67 and 146).

In other cases, however, a group of dykes has a radial disposition about a plutonic centre, as in the island of Rum. Here the tension resulted from the thrust of the magma against the roof (Fig. 151).

Usually the dykes in any one swarm are petrographically of the same type, and bear witness to the existence underground of extensive sources of (usually) basaltic magma. But the fact that the Cleveland dyke in the north of England, for example, can be traced almost continuously for 130 miles must not be taken to prove that the basin from which the magma was drawn necessarily extended over the same distance. Sometimes the internal structure of a dyke-rock suggests that the magma has been injected horizontally rather than vertically. Clearly, the fact that individual sheets, often only a foot or two in thickness, can be traced for such long distances, proves not only that the magma was exceptionally mobile, but also that it was injected rapidly. Successive injections of the same type of magma into the same dyke-fissure results in a multiple dyke. On occasion the same fissure has been followed by two or more injections of different types, giving composite dykes. The most general case is that in which an initial injection of basaltic magma has been split centrally by a later injection of granitic material: the

¹ The Great Dyke in Rhodesia, although called a "dyke," stands apart in a category of its own, on account of its thoroughly abnormal dimensions: it is three miles thick and its outcrop is 300 miles long.

former is typically black and finely crystalline in the hand specimen, while the latter is often much lighter coloured, often red, and carries relatively large crystals of quartz and feldspar. Examples of both multiple and composite dykes of Tertiary age occur in Arran!

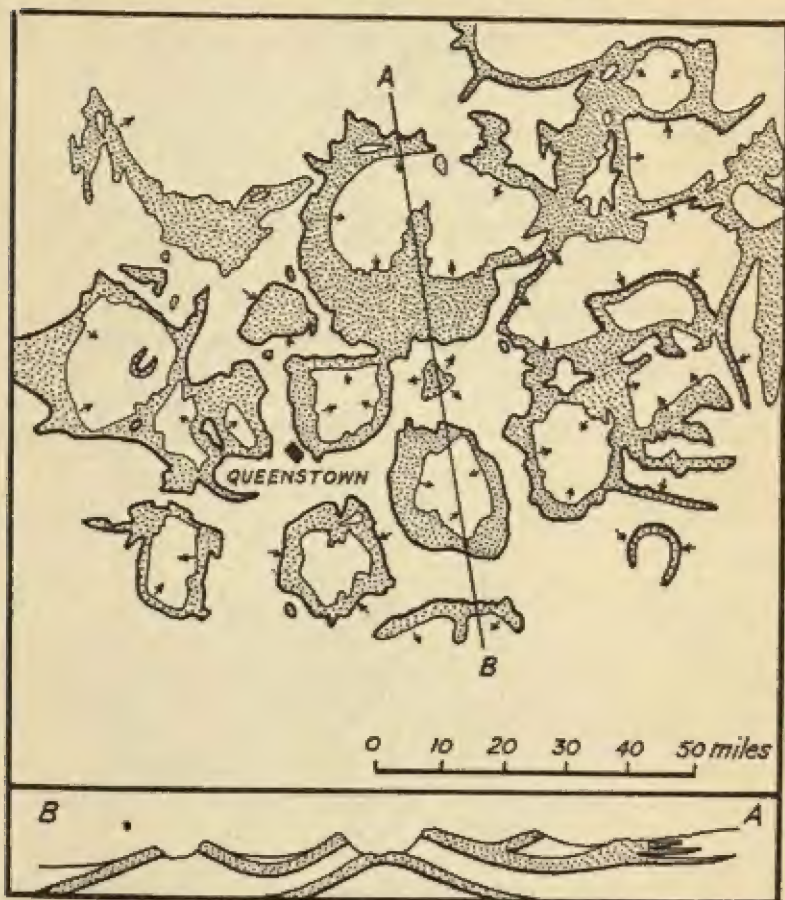


FIG. 66

Sketch map and section (vertical scale exaggerated) of thick Karpo dolerite sills intruded into sediments of the Beaufort Series, South Africa.

(After Rogers and du Toit.)

and Skye,² and are well displayed also in the north-easterly dyke-swarm of southern Jersey, Channel Islands.

¹ Gregory, J. W., and Tyrrell, G. W., *Proc. Geol. Assoc.*, xxxv (1924), p. 413 and Pl. 26.

² Harker, A., "The Tertiary Igneous Rocks of Skye," *Mem. Geol. Surv.*, 1904, pp. 201 and 207.

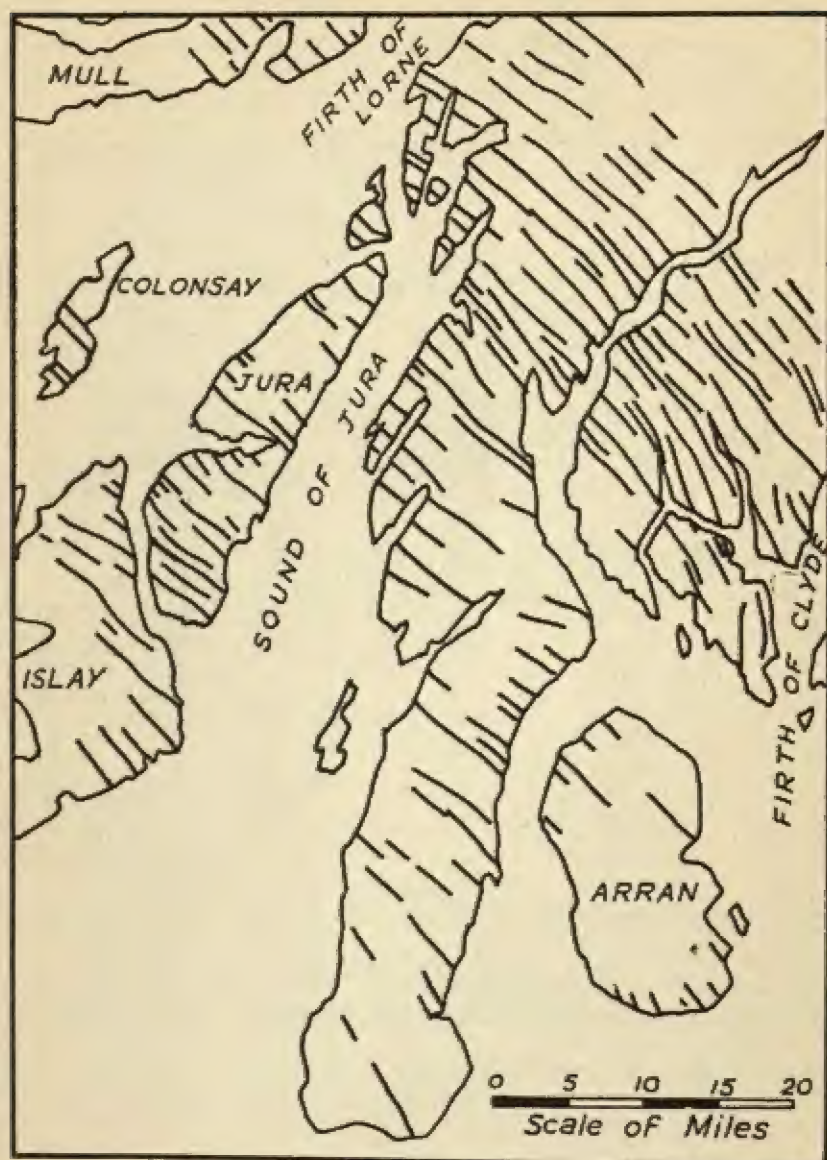


FIG. 67

Sketch-map of south-west Highlands, showing a system of north-west basic dykes (of Tertiary age) following earlier and parallel lines of weakness.

(After H.M. Geol. Survey.)

(b) **Sills.**—The three-dimensional form of a sill is the same as that of a dyke; but the attitude is different. Sills are essentially horizontal as intruded, though subsequent tilting or folding may throw them into any attitude—including the vertical. When the country-rock consists of stratified formations, the sill is normally injected between the bedding planes, and is thus concordant with them. It thus behaves at outcrop as if it were a part of the stratigraphical succession, and difficulty may be experienced in deciding whether a given sheet is sill or lava-flow. In some cases the mass-characters of the igneous rock may be sufficiently distinctive (see p. 144); otherwise the following observations may be helpful. Although sills may keep to one horizon for considerable distances, they do sometimes transgress suddenly to a higher or a lower horizon, in a manner which would be impossible for a lava-flow. Similarly vein-like offshoots, particularly into the rock *above* the igneous sheet, would indicate that the latter is a sill rather than a flow, though sometimes sills have been injected into the mud on the sea-floor, and may simulate lava-flows very closely as regards such features as vesicularity and contact alteration of the adjoining sedimentary materials.

As with dykes, sills may be multiple and, in other instances, composite. Again they consist dominantly of consolidated basaltic magma, and sills occur extensively underlying the areas of vast basaltic outpourings, noted above. They are also noteworthy in the Karroo in South Africa, not only on account of their dominance of the characteristic scenery, but also of the extraordinary extent of some of the individual sills: some extend over areas of from 3,000 to 5,000 square miles. The dissected outcrop of one of these giant sheets is shown in Fig. 66. It should be noted that the remarkable undulations, causing basin- and dome-like structures are not characteristic of sills in general.

In Britain, the best known and largest sheet is the Great Whin Sill (p. 435).

LENS-SHAPED INTRUSIONS

(a) **Laccoliths.**—These may be regarded as a special case of sills, in which the intrusion of viscous magma along a plane of weakness has caused an uparching of the strata above the intrusive mass. Ideally the floor remains flat; and in the classic description of intrusions of this type, from the Henry Mountains, Utah,¹ it was suggested that the laccolith was fed by means of a central pipe.

¹ Gilbert, W. S., "The Geology of the Henry Mountains," *U.S. Geol. Surv.*, Washington, 1877.

This is, however, hypothetical, and it appears more likely that the intrusion is fed by, and is a local modification of, a sill. The hydrostatic pressure of the magma is believed to have caused the uparching of the roof.

In sills the lateral dimensions are very great compared with the thickness; but in the laccolithic type of intrusion, the latter varies between one-third and one-seventh of the diameter. Laccoliths may be multiple, as in the case of the so-called cedar-tree laccoliths. The gabbro of the Cuillin Hills in Skye may be of this form.¹

(b) **Phacolith.**—This name is applied to a lens-shaped intrusion of concavo-convex shape situated in the core of an anticline. The phacolith owes its shape to intrusion into pre-existing folded strata, while the laccolith, in theory, *causes* the arching of the roof. The type phacolith forms the Corndon, a gabbroic or doleritic intrusion occurring in the Shelfe district of Shropshire.²



FIG. 68

Diagrammatic E.-W. section across the Bushveld complex, Transvaal. A red "granite" overlies the basic rocks (chiefly norite). Various members of the Transvaal system, into which the lopolith is intruded, are indicated as follows: *stippled*, Black Reef Quartzite; *cross ruled*, Great Dolomite; outcrops of Pretoria Series above intrusion, P P P. (After Daly, simplified.)

(c) **Lopoliths.**—Intrusions of this type are the converse of the phacolith-type, as they have the concavo-convex shape, but are convex downwards, that is the central part of the intrusion has been warped downwards. Some of the greatest basic intrusions in the world are of this type: thus, the Bushveld Complex in the Transvaal extends over a surface area of 20,000 square miles, and has a diameter of 200 miles (Fig. 68), while the Sudbury lopolith and the Duluth gabbroic complex are other outstanding examples. The term lopolith was first applied to the Duluth intrusion.³

As explained subsequently, these great lopoliths are of a composite and multiple character, and often display a layering of the component rock-types, to a marked degree. Normally basic and ultrabasic rocks make up the greater part of the complex, with the latter occurring near the floor; while granitic rocks form the highest parts of the mass. These giant intrusions must have resulted from a

¹ Harker, A., "Tertiary Igneous Rocks of Skye," *Mem. Geol. Surv.*, 1904, p. 87; but see also Richey, J. E., in "Tertiary Volcanic Centres," *Brit. Reg. Geol.*, 1935, p. 88.

² Harker, A., *Natural History of Igneous Rocks*, 1909, p. 77; and Blyth, F. G. H., "Intrusive Rocks of the Shelfe Area," *Quar. Journ. Geol. Soc.*, xcix (1943), p. 169.

³ Grout, F. F., *Amer. Journ. Sci.*, cxi (1918), p. 516.

widespread foundering of a section of the crust, and the upwelling magma almost certainly broke through to the surface in places to give subaerial flows.¹

INTRUSIONS OF RING COMPLEXES

Just as lavas can be referred to two main types of extrusion, the one of a widespread character (plateau lavas), and the other of a central and localized type (cone volcanoes), so with intrusive complexes. The dyke swarms and widespread sills are of the first kind and stand in strong contrast to the central type complexes, in which the full force of igneous activity was brought to a focus over a small area. The classical area for studying this type of complex is in the Inner Hebrides of Scotland, the chief individual centres occurring

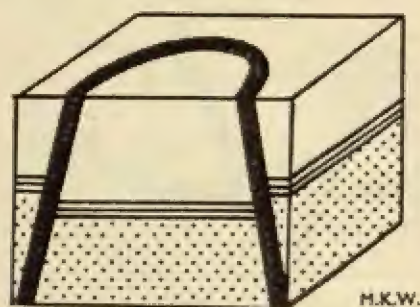


FIG. 69

Block-diagram of a single ring-dyke injected through horizontal strata.

in Mull, Skye and Ardnamurchan.² From the example in Mull, it is inferred that the intrusive complex represents the basal wreck of a large central type volcano.

The crustal forces operating in central complexes result in the formation of characteristic crescentic intrusions. Only their essential characters are considered here, since examples are described in greater detail in the last section of this book.

(a) **Ring-dykes.**—This term covers intrusions which have arcuate outcrops, the radius of which seldom exceeds two or three miles. The contact between the intrusion and the wall-rock dips outwards as shown ideally in Fig. 69. In a ring complex several such

¹ Daly, R. A., "The Bushveld Igneous Complex," *Bull. Geol. Soc. Amer.*, xxxix (1928), pp. 703-768.

² Richey, J. E., "Tertiary Ring Structures in Britain," *Trans. Geol. Soc., Glasgow*, vol. xix (1931-32), p. 45.

³ Billings, M. P., "Mechanics of Igneous Intrusion in New Mexico, Hampshire," *Daly Volume, Amer. Journ. Sci.*, 1945, p. 40, with references to literature.

intrusions, varying in width from several yards to about a mile, form concentric outcrops, with the earlier members towards the outside, and the later ones towards the centre of the complex. The last intrusion to be emplaced may have the form of a ring-faulted boss as, for example, in Ardnamurchan (Fig. 149). Some ring-dykes seem to have broken through to the surface, for they are fine-grained, flow-banded, and may show the phenomenon of explosion brecciation, especially in the case of the more acid rocks.¹

(b) **Cone-Sheets.**—The Tertiary intrusions of the Inner Hebrides provide many examples of a form of intrusion termed *inclined sheets* by Harker, and *cone-sheets* by E. B. Bailey.² These are inwardly dipping sheets, having the form of segments of concentric

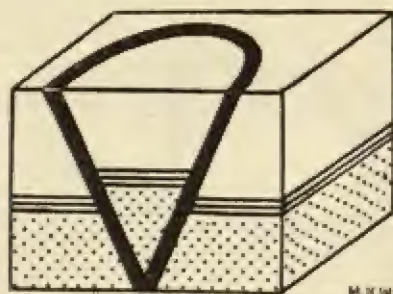


FIG. 70

Block-diagram of a single cone-sheet.

cones arranged about plutonic centres (Fig. 70). Screens of country-rock separate the cone-sheets from one another. This form of intrusion is hardly known outside the British Isles, and within this area, the examples are all of Tertiary age. Both cone-sheets and ring-dykes develop above the nose of an advancing bullet-shaped plug of magma.³ As the outcrop of the intrusive rock in both cases tends to form a closed ring, the central plug of country rock must have been displaced in order to make room for the intrusive rock. Field observations prove that ring-dykes expand, while cone-sheets narrow downwards. In the former case, therefore, the central plug must have sunk away; while in the latter case it must have been pushed up, to allow the magma to rise (Figs. 69 and 70). For simplicity we have illustrated only one example of each: but in the British Tertiary Province they occur in amazing complexity. There may be a dozen

¹ Richey, J. E., "Association of Explosive Brecciation and Plutonic Intrusion in the British Tertiary Igneous Province," *Bull. Volc., Série II* (1940), p. 157.

² "Tertiary and Post-Tertiary Rocks of Mull," *Mem. Geol. Surv.*, 1924, p. 306.

³ *Ibid.*, p. 11.

ring-dykes and scores of cone-sheets around a focal point lying above the source of magma from which they were derived.

(c) **Cauldron Subsidence Intrusions; Bysmaliths.**—One further type of intrusion must be mentioned here, for it also is connected with a type of ring-faulting. As defined by Iddings¹ a bysmalith is an injected body, having the shape of a cone or cylinder, which has either penetrated to the surface or terminates in a dome of strata like that over a laccolith. The "plutonic plug" of Russell² is a similar conception. Vertical displacement with faulting is the characteristic of this method of intrusion. Mount Holmes, in Yellowstone Park, is cited by Iddings as a type. The bysmalith appears to be genetically related to the laccolith, but owes its cross-cutting

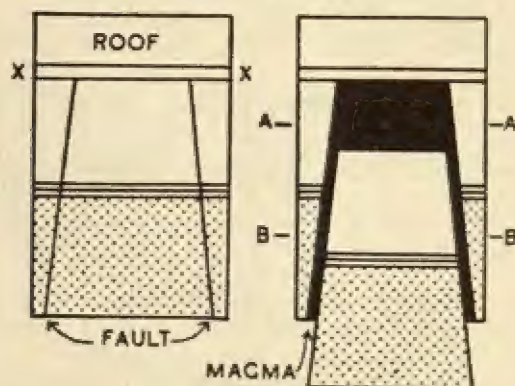


FIG. 71

Diagram sections to illustrate intrusion by cauldron subsidence.

relationship to the invaded formations to the relative incompetency of the latter to resist the passage of the magma, and to the greater speed of injection.

It is clear that if the roughly cylindrical fracture of Fig. 71 had failed to reach the surface, or alternatively, if the sinking block had been terminated upwards by a horizontal plane of weakness (X in Fig. 71), a space would be formed *above* the sinking block and into it magma would be drawn. On consolidation this intrusion would be of cylindrical form, of circular cross section (as at level A in Fig. 71; it would have a flat floor, and at a certain level (as at B) it would give place to a ring-dyke. Such movements are referred to as "cauldron subsidences" and they are due to "piston faulting." The classical British example occurs at Glencoe in South-West Scotland, described in a subsequent section.

¹ *Journ. of Geol.*, vi (1898), p. 707.

² *Ibid.*, iv (1896), pp. 23-43.

The large ring-dykes and granitic masses which have been intruded as a result of displacement following ring-faulting, form a transition between the intrusions described so far, in which the form and mechanism of intrusion are reasonably well understood, and the great subjacent intrusions, with steeply plunging contacts which continue downwards to unknown depths, and whose three-dimensional shapes and mode of origin have occasioned so much controversy. There is certainly scope for wide differences of opinion on this

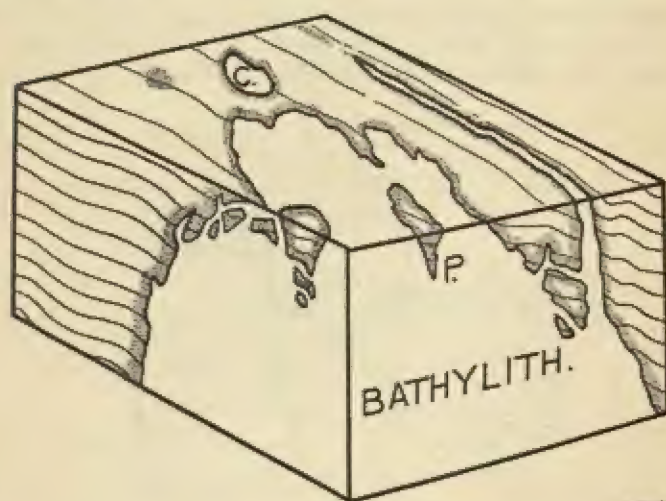


FIG. 72

Block-diagram showing the features of an ideal batholith (or bathylith). P, Roof pendant, C, Cupola, Metamorphic aureole stippled. (*Modified from R. A. Daly.*)

major problem of petrology, and for markedly different interpretations of the field evidence.

SUBJACENT PLUTONS

(a) **Batholiths.**—This term was introduced by Suess to connote the major, deep-seated intrusive masses of very large size occurring typically in the great mountain ranges, and generally elongated parallel to their tectonic trend. Their roofs may be dome-shaped, their walls steeply inclined, generally in such a manner that, when exposed by deep denudation, they either maintain their diameter, or grow broader with increasing depth.

The stripping off of this roof by denudation may, in the early stages, disclose isolated, irregular outcrops of igneous rock, which by

reason of their small size, convey no hint of the immensity of the pluton lying at no great distance beneath the level of the ground. At a later stage, the isolated outcrops connect up, while the intervening stretches of highly metamorphosed roof-rock are reduced to small islands (*roof-pendants*). In addition to, or in place of a main outcrop, "cupolas" may rise from the hidden batholith, as satellitic intrusions in the country rock. The roofs of batholiths and laccoliths are similar in general form, and in the absence of definite evidence as to the character of the lower parts of the intrusion, the non-committal term **Dome** is frequently used.

(b) **Stocks** differ from batholiths only in size, and in some cases are merely cupolas exposed by the incomplete unroofing of a batholith. They may be defined as subjacent bodies less than 40 square miles in area, which have cut across, and apparently replaced,

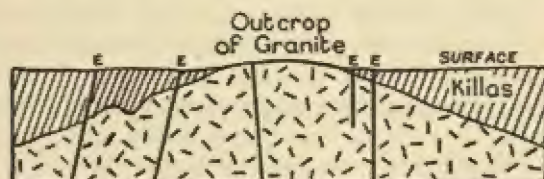


FIG. 73

Section through a granite dome intrusive in the killoes of Cornwall and penetrated by dykes of elvan (E). (After MacAlister.)

the invaded formations. Like batholiths they have steeply plunging contacts and no visible floor.

(c) **Boss** is the term applied to stocks of circular cross-section.

THE PROBLEM OF THE INTRUSION OF PLUTONS

According to the original definition given by Suess¹ batholythic intrusions originate by the melting and assimilation of a portion of the invaded formation. Michel Lévy had reached the same conclusion from his studies of French intrusions. The universal acceptance of Suess' term, however, does not imply general agreement as to the mechanism involved in their formation. In fact, opinion is sharply divided on this point.

The **space problem** concerning the origin of these major plutons is very simply stated: if such vast masses of material are intruded, what becomes of the equally immense quantities of rock, the place of which has been taken by the granite? There are two main alternatives. Firstly, the invaded rock may not, in fact, be displaced

¹ *Sitzungsberichte der Wiener Akademie*, vol. civ (1895), p. 52.

at all, but replaced *in situ* by metasomatic processes. In other words, the original rocks have been converted into granite by the minimum addition of new material from deep-seated sources. The attractiveness of this conception lies in the neat manner in which it disposes of the space problem: it just does not arise. There is at the present time most lively controversy over the reality and extent of this process of granitization of pre-existing rocks, which is considered later in the section dealing with the origin of the acid plutonic rocks.

Failing an origin by replacement, then batholithic rocks must have been emplaced by *displacement* of the invaded formation. This may be effected in several different ways.

The magma, generally granitic, may shatter, displace and incorporate large and small fragments of the roof- and wall-rocks by a process of **magmatic stoping**. The initial shattering, according to R. A. Daly,¹ is brought about by the strain caused by the differential expansion of the cold country rock when brought into contact with the very hot magma. Since solid rock is more dense than a liquid of its own composition, displaced blocks of most rocks tend to sink, and according to their nature they may actually melt, or react with the magma, and eventually disappear. These inclusions of country rock, or **xenoliths** as they are called, are therefore most abundant in the marginal facies of the intrusion, since it is only towards the margins that freezing of the magma stops further movement of the xenoliths, and also puts a stop to their complete dissolution. The difficulty of assessing the extent of stoping is obvious. For every one xenolith frozen into the "crust" of the intrusion, a host may have been completely assimilated and all direct evidence of their presence may thus be effectively removed.²

Two important consequences result from stoping: firstly, room is thus made for the advancing magma; and secondly, important changes may be effected in the composition of the magma, and new rock-types may thus be brought into being. Several probable cases are discussed in due course.

The wholesale removal of the invaded rock may be achieved by down-faulting of whole blocks, on a different scale altogether from those incorporated by stoping. Thus some of the granite masses in western Scotland are believed to have been emplaced by ring-faulting and **cauldron subsidence** (see Fig. 71). The granitic magma in such cases probably moved upwards by way of the ring-

¹ *Igneous Rocks and the Depths of the Earth*, 1933, p. 267.

² Wells, A. K. and Wooldridge, S. W., "The Rock Groups of Jersey, with special reference to Intrusive Phenomena at Ronéz," *Proc. Geol. Assoc.*, xlii (1931), p. 215.

fractures, and consolidated above the central, down-faulted block. The details of this mechanism were originally worked out in Scotland, with special reference to the Glencoe and Ben Nevis granites; but it is at least possible that many other boss-like masses, of circular to ovoid cross-section, originated in this way. The fact that some concordant intrusions come into position by thrusting aside the wall-rocks, or by uparching the roof-rocks, has long been known; but the possibility that a similar mechanism may operate in the case of the subjacent intrusions also has been seriously considered only since about 1925. At this time Hans Cloos published some of the first accounts, not only of the external form, but also of the internal structure of the batholithic rocks.¹ Since then E. Cloos, R. Balk and others have made structural studies of a number of plutonic masses, especially in the U.S.A. The correct interpretation of the internal structures throws light on the mechanism of intrusion. It serves another useful purpose in demonstrating that many granites have crystallized from material which, if not a hundred per cent magmatic, was sufficiently fluid at one time to develop flow-structure. This is obviously of importance when considering the metasomatic or magmatic origin of a pluton.

Internal Structures in Subjacent Intrusions.

Two structural elements are involved: firstly, the lineation of individual crystals and inclusions due to flow movements; and secondly, jointing due to fracturing after consolidation. A comprehensive account of these phenomena is given in an important monograph by R. Balk.²

Flow Structures develop as a consequence of the alignment of crystals and xenoliths during the act of intrusion. With regard to the first, the phenomenon is most clearly demonstrated by crystals of flattened, tabular habit, notably by feldspar phenocrysts. In this country the west of England granites, for example the "giant granite" of Dartmoor and Land's End, are typical in this respect. As regards xenoliths, these are often softened sufficiently to be drawn out into "**schlieren**" which appear as dark streaks in the normal granite. As a consequence of these flow structures, layers are formed which are normally parallel to the walls of the intrusion. In an intrusion with a domed roof these flow-layers or **platy flow-structures** dip outwards from the centre of the mass, and plunge steeply downwards in conformity with the dip of the actual surface of

¹ "Tectonik und Magma . . ." *Abh. Preuss. Geol. Landesanst.*, Heft 89, p. 1, and "Einführung in die tektonische Behandlung magmatischer Erscheinungen (Granittektonik)," 1925.

² "Structural Behaviour of Igneous Rocks," *Geol. Surv. America*, Mem. 5, 1937.

contact with the wall-rocks. They may thus be almost vertical in steep-walled stocks and bosses.

It is possible for the streaking out of these flow structures in the marginal zone of the intrusion to cause heterogeneous mineral banding similar to that commonly regarded as due to regional metamorphism. In the case of such primary gneissic banding, however, other metamorphic features, such as evidence of stress and cataclasis, should be absent.

It may be possible to detect the actual direction of flow of the magma by means of the parallel orientation of crystals of prismatic habit, such as hornblende, for example, or by the softening and elongation of xenoliths. These **linear flow structures** may be combined with layering, or they may occur independently; but in any case three-dimensional exposures are necessary to distinguish between the two types. It must be realized that these flow-structures are marginal phenomena; they tend to die out towards the centre of the mass, where the rock becomes massive, and even the feldspar phenocrysts, if present, become disorientated.

Joint Structures.—Once the outer crust of the mobile mass has solidified, no further flow is possible; but beneath the crust the magma may still exert a pressure on the crust and by stretching it, produce tensional or "cross joints." Since the stretching follows the same direction as the linear flow of the previous plastic stage, the cross-joints are developed perpendicular to the linear flow direction of the latter.

There are, however, several sets of joints in a granite mass, and enough has already been said to show that their proper interpretation is dependent upon the recognition of the flow structures. Some of the more important primary jointing systems are:—

- (a) Cross joints, already described;
- (b) Longitudinal joints, striking parallel to the trend of flow lines, and probably developed as a result of weaknesses parallel to the aligned minerals;
- (c) Diagonal joints at angles of approximately 45° to the trend of the flow lines, formed as a result of the compression which operates at right angles to the flow.
- (d) Flat-lying joints, of which the origin is still obscure.

These joint directions may be followed by veins of aplite and pegmatite, or the joint planes may be coated with veneers of minerals of hydrothermal origin, thus indicating their primary origin. In the absence of such mineralization it may be impossible to distinguish between primary joints connected with the act of intrusion, and those of later origin. Prominent among the latter are planes which develop

parallel to the surface of the ground and named, rather misleadingly, exfoliation or bedding joints. In fact they may be highly perfect joint planes spaced widely apart, and occurring to a depth of many feet in the rock. Naturally only primary joints are of value for determining the possible shape of the rock-mass, and in practice

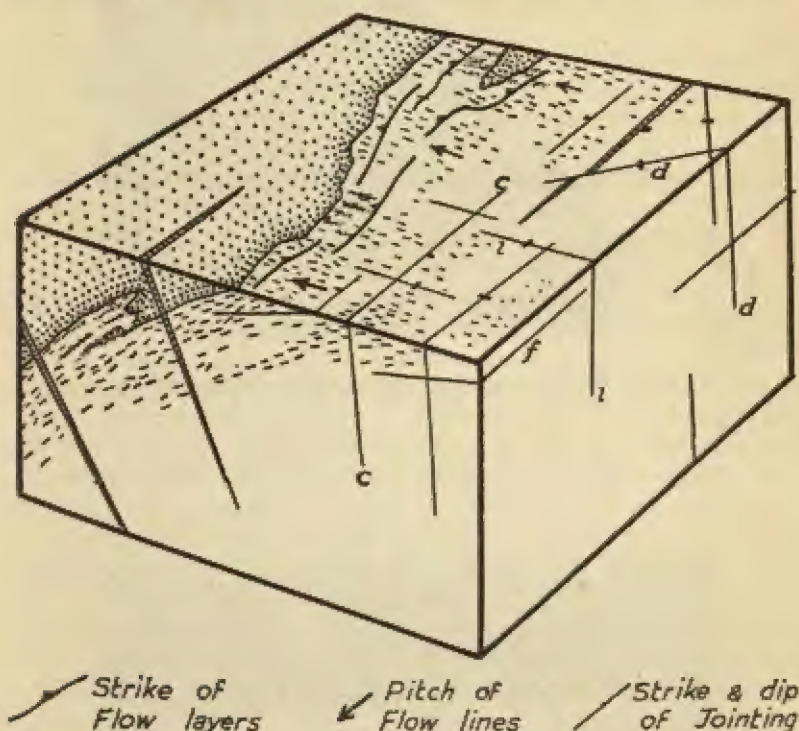


FIG. 74

Block diagram showing the relationship between flow structures and joint systems in an intrusive mass.

(c) cross joints; (d) diagonal joints; (f) flat-lying joints; (l) longitudinal joints.

most of such information is obtained from the study of flow structures combined with cross jointing alone.

Weathering takes place particularly easily along these various joint planes, so that exposed surfaces appear broken into angular blocks as shown in Fig. 75. On a freshly exposed surface it may be almost impossible to determine any directional properties in the rock, which appears massive and structureless. Nevertheless, planes of weakness, generally three almost rectangular sets, are normally present and can be detected by the experienced quarryman (Fig. 76).



FIG. 75

Mural jointing in granite, Goat Fell, Arran.



FIG. 76

Pseudo-stratification in granite due to horizontal jointing or "sheet-structure." Crabtree and Havey Quarry in Sullivan, Maine.

(After T. N. Dale.)

THE CONSOLIDATION OF MAGMA

THE original fluid raw material of igneous rocks, or magma, may have a wide diversity of chemical and physical properties. Some of these have already been described on p. 23, when the nature of igneous rocks was discussed. For the purposes of the present chapter, however, it is assumed that a magma is originally a hot fluid which is essentially a melt of complex silicates and oxides, or more correctly, one capable of crystallizing out to yield these components. In addition, small amounts of ordinarily volatile components such as H_2O , Cl , CO_2 , etc., are present. The proportions of the various elements vary greatly, mainly according to whether the magma is highly siliceous (acid), or poor in silica (basic); but always the chief components include the following: Si , Al , Fe'' , Fe''' , Mg , Ca , Na , K , and most important of all, oxygen. It so happens that in the silicates, the ratio of the other elements to oxygen is always such that their formulae may be written down in terms of oxides; for example, orthoclase $KAlSi_3O_8$ may be written as $K_2O \cdot Al_2O_3 \cdot 6SiO_2$. For this reason the convention has been adopted of stating the analyses of rocks in terms of the percentages of various oxides. It is well to bear in mind, however, that very few of these "oxides" are really present as such.

The cooling and crystallization of a mass of such complex composition is inevitably a very complicated process; but by careful study of the textural interrelationship between the minerals in rocks, it is possible to establish an order of crystallization. It is evident that the first minerals to crystallize are those which can be precipitated from a completely, or almost anhydrous melt, at high temperatures. These are the so-called **pyrogenetic minerals**, and include the majority of the silicates found as primary constituents in the basic rocks—olivines, most pyroxenes, the calcic plagioclases, etc. The separation of these pyrogenetic minerals leaves the liquid relatively enriched in H_2O and various other components of low atomic and molecular weights, which are known as the volatile, hyperfusible, or fugitive constituents. Several rock-forming minerals require for their formation a high concentration of these volatiles. These **hydatogenetic minerals** depend more on concentration of volatiles than on high temperature for their formation. Most of the alkali-rich minerals and those containing hydroxyl fall in this category.

The history of the cooling and crystallization of a magma can be divided into a number of stages, based largely on the dominance of the rôles of temperature and concentration of volatiles.

The **orthomagmatic stage** covers the separation of the pyrogenetic minerals, and in the case of a basic rock, accounts for the crystallization of the greater part of the component minerals.

This is followed by a stage during which the portion still in the fluid condition has extremely low viscosity on account of the increasing concentration of volatiles, while the temperature is still fairly high, perhaps between 400° and 600° C. This leads to the development of crystals of exceptional size, distinctive of the **pegmatitic stage** of crystallization. It is possible that the more volatile fractions may sometimes occur as gases above their critical temperatures under these conditions, especially if there is a local reduction of the external pressure within the system. Certain minerals, notably tourmaline, topaz and fluorite are especially characteristic of such gaseous, or **pneumatolytic** conditions. The products of the pegmatitic stage are commonly segregated into veins and dykes, in which case they form highly distinctive rocks (p. 202).

Finally the residual fluid may gradually pass towards the condition of low temperature aqueous solutions, and any deposition or replacement occurring at this stage is said to be **hydrothermal**.

The cooling history of a magma has been divided into more elaborate stages by some authors, who base their divisions on temperature limits. There is, of course, no direct way of determining the temperature at which any particular constituent has crystallized, but there are several mineral changes, for example the inversion of beta- to alpha-quartz, which are known to occur at fairly constant temperatures. The presence of these critical minerals, therefore, allows one to estimate approximate limits for the several stages.

These points on the "geological thermometer" are, however, too few and too much subject to variation under natural, as distinct from experimental conditions, to provide a wholly satisfactory basis on which to establish a complicated system of stages of crystallization.¹ In any case, the processes are actually continuous, overlapping of the stages is inevitable, and exact limits cannot in practice be assigned to them. In particular, it is often impossible to distinguish between phenomena produced during the pegmatitic-pneumatolytic stage and the hydrothermal stage. In some cases, indeed, it is possible only to differentiate between the products of the orthomagmatic, primary crystallization on the one hand, and

¹ A valuable summary and criticism of the many terms which have been so used, is given by S. J. Shand: "The Terminology of Late-Magmatic and Post-Magmatic Processes," *Journ. Geol.*, li (1944), p. 342.

the late-stage modifications on the other. Some of the more important aspects of these two main, broad divisions are considered below.

PRIMARY, ORTHOMAGMATIC CRYSTALLIZATION

From an early date in the history of petrology much attention has been paid to the apparent order of crystallization of the minerals in rocks. It was observed that in a large number of cases there was a definite sequence. Applying the principle that if mineral "A" encloses or is moulded upon mineral "B" the latter must be of earlier formation than the former, the commonly observed sequence was found to be: accessory minerals, ferro-magnesian minerals, feldspars, quartz. Within each group a secondary sequence was related to a constant increase in the silica content. This supposed regularity of order was summed up in Rosenbusch's "Law of Decreasing Basicity." However, many exceptions have been observed, and the principle is liable to misinterpretation since the observed order is that of completion, not the commencement of crystallization.¹ The so-called law depends on the premise that, since the initial composition of magmas varies only within quite narrow limits, there can be little variation in the order of crystallization.

As a result of the study of the thermal behaviour of slags and of silicate melts of simple composition, it is now realized that the consolidation of such melts is governed by the ordinary laws of physical chemistry and of thermo-dynamics, including the phase rule. The practical study of the subject is rendered specially difficult by the high temperatures and pressures involved, and by the fact that the great viscosity of fused silicates, when in the neighbourhood of their freezing-points, renders the establishment of equilibrium extremely slow. In addition, the magmas are of very complex composition; two or more components frequently form solid solutions; while a mineral stable at high temperatures may be converted into some other related mineral at a lower temperature.

A very great increase in the knowledge of the crystallization of silicate melts has been provided by the experimental researches of a team of workers at the Geophysical Laboratories at Washington, D.C. Such experiments are limited in their scope by reason of the complex composition of all but a few of the simplest rock-forming silicates; but at least certain broad principles have been established and a basis has been provided for the study and interpretation of the mutual relationships between these components of the crystalline rocks.

It was formerly supposed that the order of separation of minerals from an igneous melt was simply that of their freezing-points as

¹ A. Holmes, *Petrographic Methods*, 1920, p. 349.

determined experimentally. Actually this can be true only for monomineralic rocks—those consisting of but one component. The influence of one mineral upon the crystallization of another is, however, considerable; while the effects of pressure cannot be ignored, although they do not appear to be very great.

The crystallization of a rock consisting of two components is instructive, and two possible cases will be considered: first, that in which the components are quite incapable of forming solid solutions (i.e. they are immiscible in the solid state), and secondly, that in which the components are capable of forming a continuous series of solid solutions. In addition, the crystallization of a simple three-component system will be examined.

The crystallization of a pair of minerals which do not form mixed crystals can be exemplified by means of a temperature-concentration diagram, in which the relative proportions of the two components are shown in percentages by abscissae, and the temperature by ordinates. Take, for instance, the case of an anorthite-diopside melt.

The equilibrium conditions under which these two minerals will crystallize from melts of variable composition are shown in Fig. 77. Starting with pure anorthite at the point A, the addition of an increasing proportion of diopside lowers the anorthite freezing-point as shown by the curve AE, and similarly the addition of anorthite to diopside produces the curve DE. The point at which the two curves intersect is known as the *eutectic-point*, E.

Given a magma represented in composition and temperature by the point P, and subject to a falling temperature, no consolidation will take place while the temperature falls from P to P'. But at P' the constituent (here diopside) which is in excess of the eutectic proportion begins to separate in the pure form, and the system moves (by fall of temperature and change of composition of the residual liquid) along the curve P'E. On reaching the point E, the whole liquid consolidates as the eutectic, without further change in composition. If, on the other hand, we start at a point Q, representing a liquid in which anorthite is in excess, a similar result is obtained, but pure anorthite first separates. It is to be noted that the solid formed by freezing at the eutectic-point is a mechanical mixture of the two minerals, and not a solid solution: it is often characterized by the graphic texture (p. 202).

Thus it is seen that when a pair of minerals incapable of forming solid solutions (*mix-crystals*) are cooling together from a molten condition, there is a certain definite ratio of the one to the other in which they will crystallize out simultaneously in intimate admixture. Whichever mineral is in excess of this (the eutectic)

proportion, will crystallize out first. It is important to realize (1) that the order of separation of the two components is independent of their freezing-points, and (2) that over a definite interval of time the two minerals are forming simultaneously.

The eutectic ratios for certain pairs of minerals have been established. Thus from an exhaustive study of gabbroic and noritic rocks Vogt has demonstrated that for hypersthene (or diallage) and

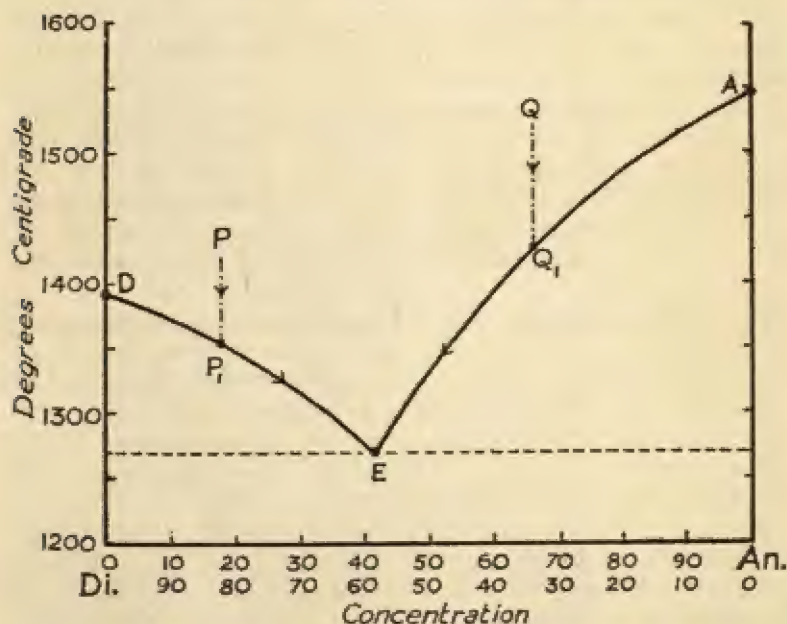


FIG. 77

Equilibrium conditions of the binary system Diopside-Anorthite.

(After N. L. Bowen.)

The explanation is given in the text.

labradorite the ratio is 35 : 65.¹ Investigations of the equilibrium conditions governing the crystallization of simple silicate melts have shown that for diopside and anorthite the ratio is 58 : 42, and for diopside and forsterite 88 : 12.²

An excellent illustration of the relation explained above is afforded by a case recorded by Harker from the Isle of Rum. In a series of rocks, consisting essentially of anorthite and olivine, the former is

¹ Vogt, J. H. L., "Physical Chemistry of the Crystallisation and Magmatic Differentiation of Igneous Rocks," *Journ. Geol.*, xxix (1921), p. 441.

² Bowen, N. L., "The System Diopside, Forsterite, Silica," *Amer. Journ. Sci.*, xxxviii (1914), p. 209.

found to have crystallized out first when the rock is rich in that mineral, while in varieties rich in olivine the reverse holds good. Only when the two minerals occur in the eutectic ratio have they crystallized simultaneously.¹

If in addition to the two minerals a third be present, say pyroxene in the case quoted, Nernst's law of the reduction of solubility between substances having a common ion,² appears to govern the order of crystallization. Thus olivine and pyroxene have the ion (Mg,Fe) in common, consequently the solubility of the olivine is much reduced, and it invariably crystallizes before the feldspar, even when not present in very large amount.³

The crystallization of two minerals that form a continuous series of solid solutions is well illustrated by the exceedingly important group of the plagioclase feldspars.⁴ In such a system, the solid and liquid in equilibrium at any temperature are of different composition, the solid being always richer in the component with the higher freezing-point. Of the two curves shown in Fig. 78, the one marked "solidus" traces the change of composition of the solid with falling temperature, while that marked "liquidus" shows the corresponding change in composition of the liquid. Temperatures are plotted vertically, while the compositions in percentages of anorthite (An) and albite (Ab) are measured on the horizontal "composition line." The course of crystallization is as follows: Starting with a melt of composition $Ab_{30}An_{70}$ at a temperature T_1 , no solid will be deposited until the point (a) is reached. At this temperature (T_2) a small amount of solid of composition (b) will be deposited. This solid (b) is in equilibrium with liquid (a) at temperature T_2 (and similarly for every other pair of points on the two curves cut by horizontal lines representing successive temperature changes). The separation of anorthite-rich solid has, however, altered the composition of the liquid phase which is richer in albite than originally. Let us suppose that the fall of temperature is temporarily arrested at T_3 , when solid (c) is in equilibrium with liquid (d). The earlier formed solid (b) will react with this liquid, the excess of the anorthite will be leached out, and equilibrium will be restored when all the solid has the composition (c). But the fall of temperature is continuous, the change in composition of the liquid is continuous, so the solid also gradually changes in composition, approaching closer and closer to $Ab_{30}An_{70}$. The whole mass will have this composition at the temperature of final consolidation, T_4 .

¹ Harker, A., "The Geology of the Small Isles of Inverness," *Mem. Geol. Surv.*, 1908, p. 85.

² Nernst, *Theoret. Chem.*, 3rd edit., 1904, p. 492.

³ Harker, A., "The Geology of the Small Isles of Inverness," *Mem. Geol. Surv.*, 1908, p. 86.

⁴ Bowen, N. L., *Amer. Journ. Sci.*, xxxv (1913), p. 583.

It must be understood that during the cooling of such a system, only a single liquid phase can exist; while if equilibrium is fully established, then there is also only one homogeneous solid phase. The difference of temperature between the commencement and

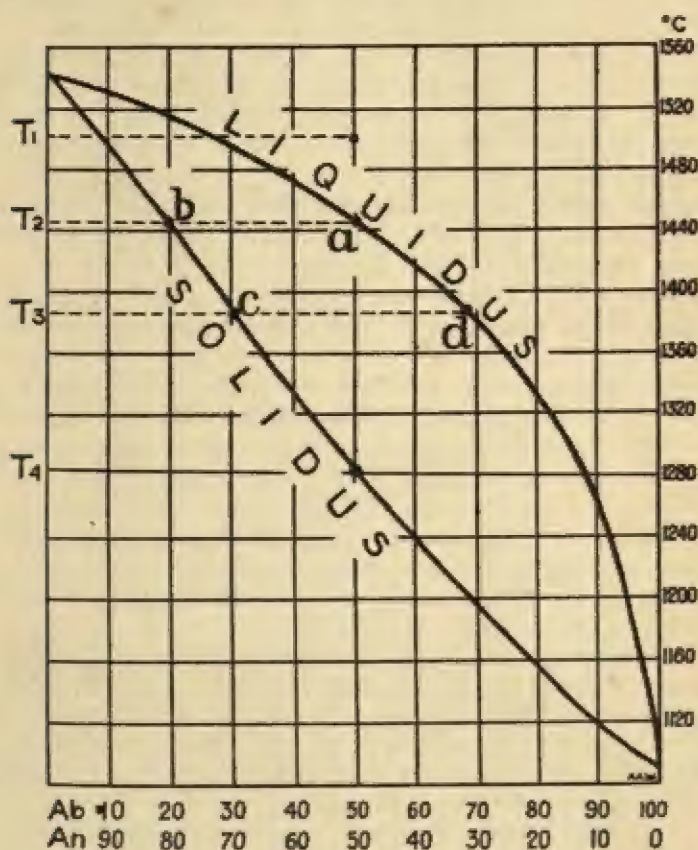


FIG. 78

Diagram to illustrate the crystallization of the plagioclase feldspars.

(After N. L. Bowen.)

(From *Amer. Journ. Sci.*, xxxv, 1913.)

completion of the act of crystallization is called the "crystallization interval" ($T_2 - T_1$). An interesting corollary is that the freezing-point and melting-point of such a system are not the same: freezing begins at T_2 while melting begins at T_4 .

Hitherto we have assumed that cooling was taking place very

slowly and that equilibrium was fully established at every stage. Such, however, is not invariably the case. It frequently happens that cooling is so rapid that, on account of the high viscosity of the melt, equilibrium between solid and liquid is not fully established, and hence the growing crystals vary in composition, and in optical and other physical characters from the centre outwards. Each successive layer or zone deposited on the nucleus retains its original character: there is no time for reaction with the liquid portion of the system to take place. In this way zoned crystals are formed, and are specially common in the plagioclase and pyroxene groups. In the former case the nucleus of a crystal having the bulk composition of labradorite may be almost pure anorthite, $Ab_{20}An_{80}$, (b) while the last drop of liquid, *i.e.*, the last zone added to the growing crystals, is nearly pure albite, $Ab_{98}An_{2}$ (Fig. 78)¹.

Although we have considered the plagioclases only, the importance of the principles illustrated by this one example may be gauged from the fact that with the exception of quartz, all the important rock-forming silicates are members of similar solid solution series and their crystallization must follow a similar course.

The order of crystallization in a system of three components can be easily treated along similar lines. For the sake of simplicity we will assume that the components do not form solid solutions, taking as an example a quartz-syenite, consisting of quartz (A), orthoclase (B), and hornblende (C). Each pair of components AB, BC and CA can form a binary eutectic, and there is in addition a ternary eutectic of three components ABC.

A system of this kind can be represented by a **triangular diagram** which is the projection of a solid model on the plane of its base. Each of the pure components is placed at the corner of the triangle, and each of the sides of the latter is divided into parts to represent percentages. Each point on the sides of the triangle then represents a mixture of two components; while every point inside the triangle represents a mixture of all three components. The ternary eutectic is one such point, though this does not necessarily lie at or even near the centre.

From each of these points representing compositions, perpendiculars are drawn proportional in length to the freezing-point of the mixture. It is obvious that there is an infinite number of such mixtures and that the perpendiculars will make a solid model rather like a trigonal prism but with an irregular upper surface. The irregularities on this surface are shown on the triangular diagram by drawing equally

¹ The composition of the solids and liquids represented by the points *a*-*d* are found by dropping perpendiculars from the point under consideration to the composition line: thus *c* has the composition $Ab_{30}An_{70}$.

spaced contours on it and then projecting them down on to the base, just as in the preparation of an ordinary contour map (Fig. 79).

In such a system the course of crystallization of a mixture represented by the point x will be as follows: Since the mixture clearly contains the component C in excess of the binary eutectic ratio BC, this excess begins to separate out, and the composition of the mixture changes along the line joining C to x and continued until it strikes the *cotectic-line* $E_{BC} E_{ABC}$, at y . The solution is then also saturated for the component B, and B and C separate together as the binary eutectic. The composition then changes along the line $y-E_{ABC}$, till finally the ternary eutectic is reached at E_{ABC} . For any other point the course of crystallization is exactly the same, except that, if the

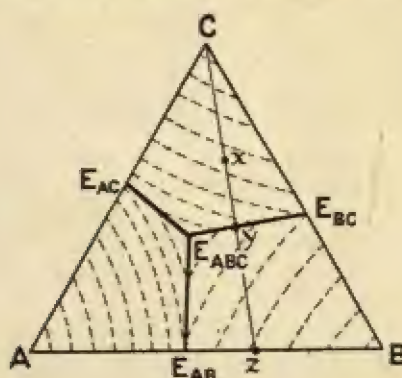


FIG. 79

Triangular diagram to illustrate the course of crystallization in a three-component system.

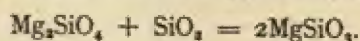
original mixture lies within the area $BE_{BC} E_{AB}$, then B crystallizes first; if it lies within $AE_{AB} E_{AC}$, then A begins to crystallize first. A line such as $Cxyz$ in Fig. 79 illustrates an important principle which is useful in the consideration of such diagrams, namely that every point on it represents a constant ratio of A to B, the proportion of C only varying (from 0 per cent at z to 100 per cent at C).

When a solid model is made on the principle outlined above, it is readily seen that each of the vertical planes standing on the lines AB, BC and CA is a binary eutectic diagram like Fig. 78. From each of the binary eutectic points E_{AB} , E_{BC} and E_{CA} a "valley" stretches down to the ternary eutectic point which is, of course, the lowest point on the surface.

The outstanding points of interest are (1) that the order of separation of the minerals is determined to a small extent by the freezing-points of the pure substances, but chiefly by their relative

concentration in the mixture, and (2) that the periods of crystallization of the several components overlap: during a definite period two components, and at a slightly later stage three components, are forming simultaneously.

Another important factor that has to be considered is the phenomenon known as **incongruent melting**. This means that when a certain mineral is heated it does not melt directly to a liquid of the same composition, but changes to another solid and a liquid, both differing from the original mineral. Thus it has been shown that orthoclase has no true melting-point, but melts to leucite and silica-rich liquid (p. 97). Similarly on heating artificial enstatite (MgSiO_3) to a high temperature (1557°C), the two products forsterite and silica-rich liquid will be obtained. It is the inverse process which is important in petrogenesis: when a melt of the composition of MgSiO_3 is cooled, the first mineral to separate is forsterite, but this becoming unstable at a lower temperature (1557°C), reacts with the liquid and is converted into the orthopyroxene, enstatite, thus:¹



If the reaction is incomplete the latter mineral is deposited as a fringe or *reaction rim* surrounding the olivine where in contact with the liquid, as may be seen in so many basic rocks. Such a pair of minerals is termed a "reaction pair."

Recently much emphasis has been placed upon the reaction principle in rock-building, that is to say, stress is laid on the mutual interaction which takes place in a cooling melt (magma) between the solid and liquid phases, *i.e.*, between early formed crystals and the residual liquid. This reaction may be continuous, giving homogeneous solid solutions, as in plagioclases, or it may be discontinuous, taking place only at definite temperature intervals. The latter type is illustrated by the replacement, completely or in part, of olivine by pyroxene, and of pyroxene by primary hornblende. Such a series of minerals, when arranged in the order in which the transformations occur, constitutes a *discontinuous reaction series*. Bowen has drawn attention to the following series: olivine \supset orthorhombic pyroxene \supset common augite \supset hornblende \supset biotite; leucite \supset orthoclase; anorthite \supset albite; common augite \supset sodic augite; common hornblende \supset sodic hornblende \supset lepidomelane.

It should be realized that almost all the rock-forming silicates are members of isomorphous groups, each one of which is a continuous reaction series; that each of these in turn participates in the changes hinted at above. Further, taking the simplest possible view

¹ Bowen, N. L., "The Reaction Principle in Petrogenesis," *Journ. Geol.*, vol. xxx (1922), p. 177.

of the course of crystallization in a natural magma, it has been established that there are at least two parallel series of changes taking place concurrently, and to some extent overlapping and interdependent. The one involves the coloured silicates (the mafic constituents) and the other the felsic components. N. L. Bowen¹ represents them thus:

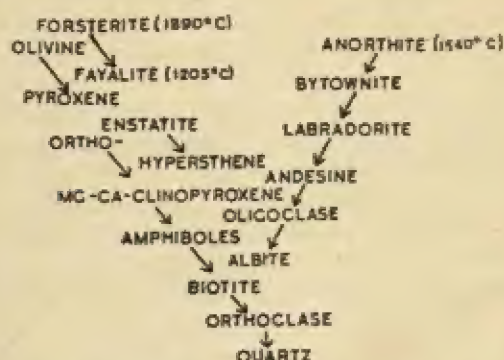


Table showing discontinuous reaction series (left-hand side) and continuous reaction series of the plagioclase feldspars (right-hand side). (After N. L. Bowen.)

In the discontinuous series represented on the left-hand side of the table above, apart from accessories the first silicate minerals to appear are the olivines, and of these, magnesium-rich precede iron-rich types.² Their separation from the magma takes place at high temperatures.

At a certain lower temperature these react with the magma and tend to be "made over" into magnesium-rich pyroxenes. These again are stable only over a limited temperature range and in turn tend to give place to monoclinic pyroxenes containing the Ca-bearing diopside molecule. So the changes suggested by the table continue.

Meanwhile at high temperatures calcic plagioclase has crystallized, and with falling temperature has reacted with the magma, changing its composition steadily towards the sodic pole—the albite end of the continuous series. The interrelation of the two series of changes is suggested by the fact that the conversion anorthite \rightarrow albite releases CaAl, while the change in the pyroxenes involves the addition of CaAl.

Brammell directs attention to the continual increase in com-

¹ *The Evolution of the Igneous Rocks*, 1928, p. 60.

² Bowen, N. L., and Schairer, J. F., "The System MgO-FeO-SiO₂," *Amer. Journ. Sci.*, xxix (1935), p. 151.

plexity of the atomic structure in passing from olivine to biotite. In olivine the structure is as simple as possible, the crystals being constructed of separated SiO_4 -tetrahedra. In the pyroxenes they are linked into chains; in the amphiboles they form bands; and in the micas they form extended sheets. The successive conversions involve abrupt changes in crystal atomic structure: each change is a passage from simple to complex.¹

THE LATER STAGES OF CRYSTALLIZATION: DEUTERIC PHENOMENA

Once we get down to the amphiboles and micas in Bowen's reaction series, the complexity of composition makes experimental work almost impossible. This is true of all the hydroxyl-bearing silicates, and to those which have crystallized from a fluid enriched in volatiles, or fugitive constituents. The very term "fugitive" implies, as Shand meant it to do, that these constituents do not, in many cases, remain as part of the ultimate rock body. They may take part in several reactions and make others possible, and yet leave no trace of their passage. Thus it is necessary to face the task of interpreting an important part of the crystallization of an eruptive rock without knowledge of either the quality, the quantity or the ultimate whereabouts of the agents involved.

The important rôle of the fugitive constituents can be judged from the following facts.

1. When volatile-rich magma is erupted at the surface as lava, the fugitives are enabled to escape rapidly, and in so doing they immediately increase the viscosity of the lava, which solidifies rapidly, either as glass, or as a cryptocrystalline aggregate. This rapid crystallization, coupled with the violent oxidation of escaping gases, accounts for the rise in temperature, amounting in some cases to a hundred or two degrees Centigrade, which is almost certainly responsible for the corrosion of previously formed phenocrysts. The significance of the vesicular and amygdaloidal structure of certain lavas, and even minor intrusives that consolidated near the surface, is too obvious, in this connection, to need stressing.

2. In some active volcanic regions there exist powerful reminders of the activities of fugitive constituents in the form of **fumaroles**, which give off intermittent or continuous streams of gases, some of which form mineral deposits by sublimation. These volatiles also cause considerable alteration of the rocks surrounding the vent.

From this visible evidence provided by volcanic activity, we turn to consider the comparable effects produced in a deep-seated

¹ Brammall, A., "Mineral Transformations and their Equations," *Science Progress*, No. 120, 1936.

environment. Here direct observation is impossible, but it is reasonable to infer the probable course of events. One of the chief difficulties is to decide whether the active solutions arise entirely as a residuum left over after the completion of orthomagmatic crystallization, or whether they have been derived from some extraneous source. When the active solutions are directly of magmatic origin, all changes in mineral composition or in texture produced by them are termed **deuteric**. This term was introduced by J. J. Sederholm,¹ and may cover crystallization or alteration phenomena appropriate to both the pegmatitic and the hydrothermal stages. In the second case the active solutions are derived usually from a later intrusion, and any modification they effect is distinguished as **metasomatic**. Not infrequently it is impossible to distinguish between deuteric and metasomatic phenomena. We may thus be guilty of extending Sederholm's most useful term beyond its original meaning. The very acid and the highly alkaline rocks are usually products of magmas rich in H_2O and other fugitive constituents, and therefore tend to exhibit deuteric phenomena on an extensive scale, and in a variety of ways.

Since deuteric phenomena arise when the rock is very nearly solidified, it is natural that they should consist to a large extent of veining and replacement of earlier formed minerals. Several of these late-stage replacement phenomena are sufficiently distinctive and important to have names of their own: albitization, analcitzation and chloritization are among the more important examples, while tourmalinization and silicification might also be considered in this category on occasion.

The term **albitization** covers a wide range of phenomena, though in essence, of course, it is simply the partial or complete replacement of earlier formed plagioclase or potassic feldspar by albite, which is stable in the presence of volatile-rich, lower temperature residual solutions. At this point we consider only those aspects of albitization which may legitimately be regarded as deuteric: we omit for the time being the widespread development of albite-rich rocks on a regional scale, exemplified by the occurrence of rocks of the spilitic suite; and similarly the conversion of basic plagioclase into albite charged with inclusions of lime-rich minerals, due to mild metamorphism of the so-called regional type. Deuteric albitization, on the other hand, involves, at an early stage, the development of the less regular types of perthitic structure. The "patch-" and "injection-perthites" are presumably formed in this way, by the action of residual solutions on orthoclase or microcline. In slightly

¹ "On Syntectic Minerals and Related Phenomena," *Bull. Comm. Géol. Finlande*, No. 48 (1916), p. 134.

different circumstances the albite forms water-clear crystals interstitial to the minerals of earlier formation, or it may be deposited as a mantle around earlier feldspars. If the latter is orthoclase or microcline, there will be a striking contrast in appearance between the core and the external zone of the crystals, and this *rapakivi structure* may be obvious in hand-specimens. If the core consists of plagioclase, however, there may be an almost imperceptible gradation towards the outer albite rim. The result may be a zoned crystal, indistinguishable from one produced by rapid cooling of an anhydrous melt. Thus there is no hard-and-fast dividing line between orthomagmatic and late-stage crystallizations: it is often impossible to say where one ends and the other begins. In fact, the distinction between the two stages only becomes apparent if the deuteric minerals are of a different nature from those of earlier formation, and if the former demonstrably replace the latter.

Analcite behaves in much the same manner as albite in many cases, especially as regards the veining and progressive replacement of feldspars. But, like all late-stage minerals, it need not necessarily be replacive, but may crystallize in the interstices between crystals of earlier formation. When this is the case, although the crystal boundaries may be plane, with no sign of corrosion or embayment, there is clear evidence of the chemical activity of the residual solutions from which the analcite crystallized, particularly when the surrounding crystals are pyroxenes. For example in teschenites the pyroxene is a typical lilac-coloured titanaugite except where it is in contact with such "pockets" of analcite: here it is rimmed with bright green aegirine-augite. Thus analcite plays a dual rôle. That which occupies these interstitial areas must be regarded as the last of the primary minerals to crystallize out; but that which so clearly veins and replaces earlier feldspar crystals, is just as definitely secondary.

This double rôle is also played by **chlorite**. The several members of the chlorite group may replace and pseudomorph olivines, pyroxenes, amphiboles and micas, generally with the development of a fibrous, and occasionally a spherulitic, habit. In certain rocks, however, pellucid grains of chlorite occur, bounded by crystal faces of the very minerals which elsewhere are replaced by it. Obviously such interstitial chlorite is primary—it has replaced nothing. Once again we are seeing the results of overlap between the final primary crystallization, and deuteric replacement.

Because of their late-stage origin, there is a widespread tendency to call such minerals as chlorite and analcite secondary, whatever their mode of origin. The only logical use of this term, however, is to restrict it to minerals which demonstrably replace others of

earlier formation. If one of these late-stage minerals has an interstitial mode of occurrence, there is no alternative to calling it primary unless, of course, there are actual relics of an earlier mineral visible.

Two particularly interesting and much debated phenomena remain for consideration: they are (1) interstitial micrographic intergrowth of alkali-feldspar and quartz occurring in certain basic rocks; and (2) the peculiar quartz-plagioclase intergrowth, known as myrmekite, which is relatively common in acid and intermediate rocks.

In regard to the first, various hypotheses have been suggested to explain the intergrowth, which is commonly called **micropegmatite**. Vogt¹ claimed that micropegmatite results from the simultaneous crystallization of orthoclase and quartz in eutectic proportions in residual solutions. Other workers have found evidence that similar structures arise from the introduction of alkalis and lime into highly siliceous rocks; that is, micropegmatite may result from the feldspathization of quartz.² The converse process—silicification of feldspar—has also been suggested as a further possibility.

Both silicification of feldspar and feldspathization of quartz undoubtedly form types of quartz-feldspar intergrowth, though it is doubtful if the resulting structures are as geometrically perfect as those resulting from simultaneous crystallization. In the case of interstitial micropegmatite, however, any replacement hypotheses appear to be untenable, since the intergrowths are moulded upon, and radiate from, unaltered and euhedral feldspar crystals. In other words, the micropegmatite crystallizes, without any replacement, from an interstitial residuum.

Myrmekite is quite different, both in composition and in mode of occurrence. It consists of lobate patches, often described as cauliflower-like in form, of plagioclase riddled with small "vermicules" of quartz. The lobes normally have grown on plagioclase into microcline (Fig. 80). F. Becke³ has estimated that the amount of quartz in the intergrowth increases as the host plagioclase becomes more basic. This fits in well with the hypothesis that the quartz is released as a result of the replacement of potassic feldspar (the formula of which may in this connection be represented by $K_2O \cdot Al_2O_3 \cdot 6SiO_2$), by plagioclase which contains the anorthite component, represented by $CaO \cdot Al_2O_3 \cdot 2SiO_2$.

Besides releasing silica, this reaction would also release potassium which is displaced by the incoming sodium and calcium ions. The

¹ "The Physical Chemistry of Crystallization and Magmatic Differentiation of Igneous Rocks," *Journ. Geol.*, xxxi (1923), p. 245.

² Reynolds, D. L., "Demonstrations in Petrogenesis from Kiloran Bay, Colonsay," *Min. Mag.*, xxiv (1936), p. 367.

³ "Über Myrmekit," *Tscherm. Min. Petr. Mitt.*, xxvii (1908), p. 377.

potassium probably contributes to the formation of mica as a by-product of myrmekite formation.

The intergrowths are most abundant along plagioclase-orthoclase, or plagioclase-microcline boundaries, so that J. J. Sederholm¹ has suggested that the juxtaposition of these two contrasted feldspars is essential for the formation of myrmekite. He calls such reaction

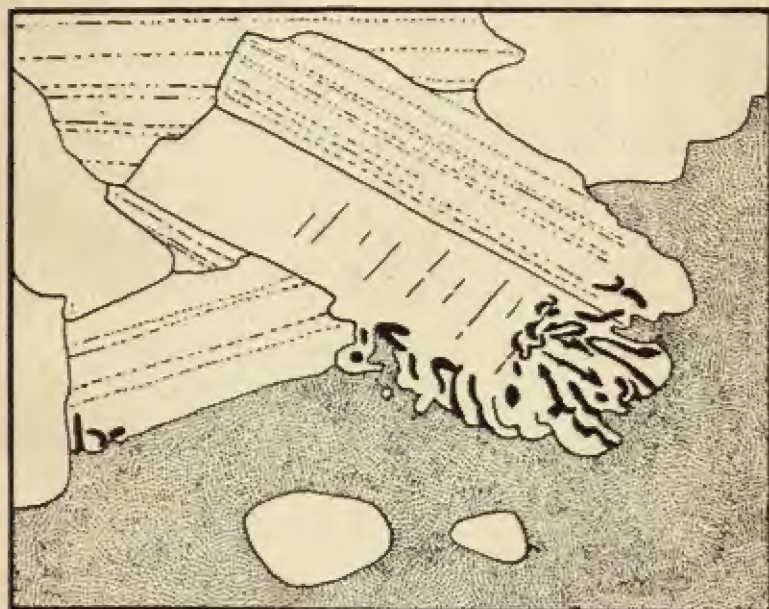


FIG. 80

AKW.

Myrmekite intergrowths of plagioclase (with twinning indicated) and vermicular quartz (black), penetrating microcline (stippled). The latter contains two rounded blebs of clear quartz, Dancing Cairn, Aberdeen.

products formed between two neighbouring solid phases, *syntectic*. Almost certainly the necessary reagents migrate along intercrystal boundaries, and it is possible that they may not all be entirely deuteric, for myrmekite is often found in granite adjacent to later basic intrusions, and thus it may be partly of metasomatic origin.

Myrmekite is just one of several phenomena which arise by interaction between adjacent mineral grains. Corona structures, which have a similar origin and are most commonly developed in the gabbroic rocks, are described in due course.

¹ "On Syntectic Minerals and Related Phenomena," *Bull. Comm. Géol. Finlande*, No. 48 (1916), p. 134.

PART III

*SYSTEMATIC DESCRIPTION
OF THE
IGNEOUS ROCKS*



CHAPTER I

ROCK CLASSIFICATION AND NOMENCLATURE

(1) *Requirements of a Rock Classification.*

The main purpose of rock classification is to provide a key for the identification of hand specimens. The unit of study is the hand-specimen, which is to the petrologist what the individual plant is to the botanist. The wider knowledge of the larger unit—the rock-body—follows after, and is completely dependent upon, the study of individual specimens: therefore the correct identification of the latter is the primary consideration. Uniformity of nomenclature is an essential basis of all petrological research, particularly that of a quantitative nature. A worker interested in the distribution of, say, basalts in time and space, is sadly frustrated if half the rocks he should take into consideration are disguised under other names; yet such is the case today. In one well-known text-book¹ a table occurs showing the mineral composition of nine rocks which conform to the author's definition of "andesite"; but of these, only one was so named by the petrologists who originally described and named them—the others all bore different names.

The trouble arises from the fact that many of the commonest rock-names now in use are of considerable antiquity; they have been defined and redefined many times, and may be used in several different senses.

There are several excellent schemes of classification in use today, and all serve some useful purpose; but no one of them can be expected to serve the needs of all petrologists, for all purposes. A classification which may be wholly satisfactory for one purpose, may be quite inadequate for another. There is much to be said for establishing (at least) two schemes: one to serve the needs of the student, the field geologist and the maker of geological maps; and the other for the petrological specialist. For the non-specialist it seems to us self-evident that both classification and nomenclature must be based on the visible characters of the rocks—on their mineral-content and texture.²

¹ Johanssen, J., *Descriptive Petrography of the Igneous Rocks*, vol. iii (1937), p. 167.

² The "fabric" of American petrologists is synonymous with our "texture": both involve the intimate relationship between the components of the rock.

(2) Classification on a Chemical Basis: the Norm.

It should be clearly understood, however, that mineral composition is the visible expression of the even more fundamental chemical constitution; while the texture is, if properly studied, a record of the cooling history of the rock. In some petrological studies the chemical aspects become of paramount importance, while the actual mineral composition and textural qualities become of secondary importance. That is, the visible characters which give the rock distinctiveness in the hand-specimen and thin section become of less significance than chemical relationships deduced from a close study of chemical analyses. In such studies a quantitative scheme of classification based on the chemistry of the rocks must be used. One such scheme, devised by four American petrologists, Cross, Iddings, Pirsson and Washington (and therefore usually referred to as the "CIPW" classification¹), is based upon the recasting of the chemical analysis from percentages of oxides, etc., into amounts of "standard minerals." This expression of the composition of a rock in terms of these largely hypothetical standard minerals is its **norm**. The advantages of such schemes are numerous: practical difficulties arising from the presence in the rock of natural glass or of material too finely crystalline to be resolved, are eliminated; the chemical affinities are clearly shown; the "pigeon-holing" of the specimen is accurate and precise; while problems of nomenclature need not arise, for in such schemes a symbol, comparable with a chemical formula, can be used instead of a name.

Since the norm is only another, and very instructive way of expressing the chemical characteristics of a rock, it may appropriately be used when comparing rocks which, though of closely similar chemical composition, consist of very different mineral assemblages, owing to differences in their cooling history. Before a solid phase can separate as a mineral species, the magma must become saturated with the appropriate chemical constituents. Other factors in addition to composition, however, enter into the conditions of equilibrium, notably temperature and to a less extent, pressure. The concentration of volatile fluxes is a more incalculable factor, but certainly exerts a controlling influence on the crystallization of many minerals. Solely on account of the conditions during cooling, then, a magma of a certain composition may give rise to several distinct mineral assemblages. This phenomenon is known as **heteromorphism**. Rapidly cooled rocks may be expected to show a mineral assemblage characteristic of high temperature crystallization; while a plutonite of deep-seated origin, on account of its slower

¹ *The Quantitative Classification of Igneous Rocks*, Chicago, 1903.

cooling, should consist of an assemblage that had attained equilibrium at a lower temperature. Obviously the nature of the research work and the particular aims in view will determine whether the chemical similarities between two such rocks are to be compared by calculation of the norm; or whether attention is to be concentrated on their contrasted **modes**,¹ which will betray something of their cooling histories.

As an illustration we may quote the case of hornblende.² As was shown above, there is a close chemical relationship between the amphiboles and pyroxenes, while the physical conditions that favour the crystallization of the one, often inhibit the formation of the other. More specifically, if the components of hornblende are available, this mineral will appear in the rock only if the environment is favourable; otherwise almost exactly the same components may appear as the pyroxenes augite and a Mg-rich orthopyroxene in association. Similarly, if the chemical compositions are carefully compared it will be seen that the following cases of heteromorphism may be expected:—

Biotite and quartz may be represented by orthoclase, hypersthene (or olivine) and magnetite.

Hornblende→augite and orthopyroxene.

Hornblende→orthopyroxene, olivine, plagioclase.

Augite→calcic plagioclase, olivine, diopside, magnetite.

Biotite, orthoclase, hornblende→leucite, olivine, anorthite and magnetite.

Biotite, plagioclase→orthoclase, nepheline, augite, magnetite.

Plagioclase (sodic), olivine, diopside→nepheline, hornblende, plagioclase (calcic).

Orthoclase, nepheline, augite→leucite, plagioclase, melilite and olivine.

* One other matter arises in connection with the calculation of the norm. The results may be expressed by a symbol, and although the latter cannot remove the need for rock-names, it is in effect a concise statement of composition, and as such is far superior to most rock-names, particularly the type of name which tells one nothing of the chemical or mineralogical composition of the rock, but only suggests the name of the place where the original specimens were obtained. Rock-nomenclature is overburdened with "jacupirangites" and "mariupolites." On the other hand it is not particularly inspiring to refer to a rock as $XsM\alpha(25)$, and it would obviously be impossible to

¹ The mode is a quantitative statement of the actual mineral content of the rock.

² Kennedy, W. Q., "The Influence of Chemical Factors on the Crystallisation of Hornblende in Igneous Rocks," *Min. Mag.*, xxiv (1935), p. 293.

use such symbols on a geological map prepared for general use; but to anyone familiar with the excellent scheme devised by S. J. Shand,¹ the symbol calls up a most comprehensive picture of the essential character of the rock as regards degree of crystallization, the rôle of silica in it, its coloured minerals, the kinds of feldspar present and the ratio of light to dark minerals. Probably the greatest single advantage of a chemical classification over a mineralogical one is that all rocks of the same composition are automatically put in the same category, even when the rock is glassy or too finely crystalline for the minerals to be determined.

Thus, knowledge of one such quantitative scheme of classification is essential in petrological research; but it is natural for the student and field geologist to put more faith in the actual mineral composition—the mode—of a rock, than in invisible relationships between hypothetical components. Therefore in the more elementary treatment developed in this book, although the importance of the chemical background of the classification is fully realized, emphasis is laid on the facts of mineral composition and texture.

(3) *The Rôle of Silica Percentage in Classification.*²

In previous editions of this "Petrology" the view was taken that as the essential minerals in the igneous rocks are silicates, accompanied in many cases by free (*i.e.*, uncombined) silica, a main prop of the classification should be silica percentage. Three major categories, "Acid," "Intermediate" and "Basic," were defined in terms of stated ranges of silica percentage. This view can no longer be maintained. The terms "Acid" and "Basic" in particular remain invaluable; but though they give expression to a purely chemical conception, through constant use they have come to acquire a much wider significance than was originally implied. The most obvious measure of acidity, but by no means the only one, is the quartz-content of a rock. But two rocks of identically the same silica percentage, and therefore of exactly the same degree of acidity, may differ fundamentally in mineral composition: one may contain more than the average amount of quartz for a typical granite, while the other may contain none. In other words, a typical granite ("Acid") may contain the same amount of silica as a typical syenite ("Intermediate"). No silica-percentage limit can be chosen which will separate all Acid from all Intermediate rocks. This problem will be further considered on a later page. In view of their undoubted usefulness we retain the terms, but use them in a qualitative sense

¹ *The Eruptive Rocks*, London, 1947, p. 225.

² Wells, A. K., "Silica percentage . . . in igneous-rock Classification," *Min. Mag.*, xxviii (1949), p. 688.

only—if used in a quantitative, chemical sense, they inevitably cut right across a mineralogical classification.

The examination of thin sections suggests that certain minerals are incompatible with quartz—they never occur in association with it, and presumably were incapable of forming in the presence of free silica. Common olivine (chrysolite), leucite and nepheline are well-known instances. These conclusions have been amply confirmed by the experimental study of silicate melts. In 1913 Shand introduced the concept of **silica-saturation**, which was made one of the mainstays of his scheme of classification.¹ The whole of the Acid rocks are **over-saturated**, in the sense of containing more than enough silica to saturate all the bases present, the excess appearing as free quartz, either actual (modal) or potential (normative) in the case of rocks containing glass. In addition to these, however, many rocks in the Intermediate and even Basic categories contain a little accessory quartz, and are therefore over-saturated. It should be noted, therefore, that "over-saturated" is not synonymous with "Acid." Again, although no "Acid" rock can, by definition, be **under-saturated**, many "Intermediate" and "Basic" rocks show this quality by the presence of a feldspathoid acting as proxy to feldspar, or by the occurrence of olivine or certain unsaturated accessory minerals. This principle also will be developed in due course.

(4) *Mineral Composition.*

Most igneous rocks consist of a small number of essential minerals—usually three to six. To these must be added a number, sometimes quite large, of accessory constituents, which are only brought to light by careful systematic search. This involves crushing a quantity of the rock—the greater the quantity, the better the result—and separating the accessories from the predominant essential components by a technique that is essentially the same as that used in the examination of a sedimentary rock. The accessory minerals are usually of high specific gravity compared with the other components like quartz and feldspar, and advantage is taken of this fact to concentrate and separate them from the latter. The granitic rocks seem to be richer in these accessories than the basic rocks. Although, for example, the Daftmoof granite is a normal type, it yielded twenty different accessory minerals when studied in this way.²

By contrast some few rocks contain one essential mineral only, and in consequence are termed *monomineralic*. The most widespread of these consists (so far as essentials are concerned) of basic plagi-

¹ Shand, S. J., "The Principle of Saturation in Petrology," *Geol. Mag.* (1915), p. 340. See also "Eruptive Rocks," by the same author.

² Brammall, A., and Harwood, H. F., *Min. Mag.*, xx (1925), p. 130.

class only; but other monomineralic rocks consist wholly of such minerals as olivine, pyroxene or hornblende. Anorthosite (the basic plagioclase rock) on the one hand and monomineralic rocks composed of a ferromagnesian mineral on the other, represent the two extremes of colour variation in igneous rocks. The division of minerals into two categories, light and dark, is a simple operation and the determination of the ratio of light to dark minerals present in any rock provides a possible factor in rock-classification.

The light-coloured or **felsic minerals** include quartz, feldspars and feldspathoids; while the dark or **mafic minerals** are dominantly olivines, pyroxenes, amphiboles and dark micas. Generally speaking, the felsic minerals predominate in the more acid rocks, and the proportion of mafic minerals increases as the rocks become more basic. In this sense the ratio of light to dark minerals has a considerable petrological significance. Three terms are used to indicate this ratio: the rock may be *leucocratic* (light), *mesocratic* (or mesotype—medium) or *melanocratic* (dark). To give the terms precision Shand has suggested the following divisions in his classification:—

Leucocratic—carrying less than 30 per cent dark minerals;

Mesocratic—carrying between 30 and 60 per cent dark minerals;

Melanocratic—carrying over 60 per cent dark minerals.

Apart from these arbitrary limits, however, it is very convenient to use *leuco-* and *melano-* as prefixes before recognized rock-names to indicate *relative* poorness or richness in dark minerals. Thus leucogranite and leuconorite are leucocratic varieties of granite and norite respectively: but normal norite, a basic rock, is notably richer in dark minerals than normal granite.

The percentage of dark minerals in a rock is termed its **colour-index**, and it is useful to measure this quantity whenever practicable. It is incorporated in the symbol quoted on p. 183 as (25). The colour-index may be determined by measurement on a smoothed surface of the rock or in a thin section, or it may more accurately be derived by crushing the rock and separating the "heavy minerals" by means of bromoform or other heavy liquid. If this method is used, certain minerals which are light in colour, though of relatively high specific gravity, will be included with the genuinely dark minerals. To avoid complications these are included with the latter. Among them are topaz, andalusite and corundum.

The use of feldspars in classification is no new principle: indeed they were so used by Abich over a century ago, and most schemes devised since his time give some recognition to the dominant rôle of this group of silicates, though there is considerable difference of opinion as to how they should be used. The contrasts between

orthoclase and plagioclase as regards crystallographic and optical characters are, as a rule, sufficiently striking as to make direct comparison relatively easy. As shown above (p. 86) albite has the same status as orthoclase; it is of strictly analogous composition, but is itself the end-member of the plagioclase group. Actually albite plays a rôle different from that of the other plagioclases, and the necessity for comparing the former with the latter seldom arises. But albite is often most intimately associated with orthoclase in the form of perthitic or antiperthitic intergrowths, which must be treated simply as *alkali-feldspar*, if microscopic evidence is to provide the basis of the classification. Thus in our scheme, "alkali-feldspar" comprises the several forms of potassic feldspar, the sodic feldspar, albite, and all forms of intergrowths between them. This alkali-feldspar may legitimately be contrasted with plagioclase, excluding pure albite. Some petrologists consider that a two-fold division made on this basis is adequate; but a higher degree of precision is achieved by distinguishing three series, characterized by alkali-feldspar to the extent of more than two-thirds, between two-thirds and one-third, and less than one-third respectively, of the total feldspar-content. With coarse-grained rocks, at least, it is little more difficult to measure the actual proportions with a sufficient degree of accuracy, than it is to determine which kind of feldspar is in excess of the other. In many cases an estimation by eye will give the desired result; but this is impossible when dealing with a fine-grained rock, and there the only course open is to calculate the composition of the feldspars from an analysis.

(5) *Mode of Occurrence as a Factor in Classification.*

There is still much difference of opinion as to whether the igneous rocks should be divided into categories on the basis of mode of occurrence, or not. In this connection it is necessary to stress the fact that our classification is one of rock-specimens, which, like other natural objects, must be classified through their inherent characters—their mineral composition and texture. Mode of occurrence in the field is, in this connection, of no significance whatsoever. Specimens of the same rock-type, completely identical in composition and texture, may occur in dykes with "hypabyssal" mode of occurrence, or in lava flows, with an "extrusive" mode of occurrence. It is manifestly absurd to apply two different names to the same rock, but this inevitably happens when recognition is given to a hypabyssal group of rocks. But in point of fact, those who do so find it inexpedient to apply the principle systematically, for it is impracticable to define "hypabyssal" and "plutonic" in a scientific manner. The latter is a useful general term that conveys a vague

impression of an intrusion of "major" status, that consolidated in a "deep-seated" environment, under a "thick cover." All these terms are comparative only: none of them is capable of precise delimitation—in fact nobody attempts the delimitation, because everybody knows that it is impossible to say just how big or how deep-seated an intrusion must be before it graduates from the "hypabyssal" to the "plutonic" status.

Classification cannot be based on vague impressions. From another angle, it seems neither reasonable nor scientific to base classification upon a feature, not of the rock-specimen itself, but of the nature of its environment. Knowledge of the mode of occurrence of a rock is often uncertain—it depends upon the interpretation of field evidence which may not be available. In such cases, and they are very numerous, the basis of classification does not exist and therefore it is impossible to name the rock although all its inherent qualities may be perfectly displayed: all the data are there for naming the rock with any desired degree of accuracy. As an illustration of the inconsistencies that inevitably result, it may be instructive to consult an authority who at least pays lip service to the mode-of-occurrence principle.

Johanssen classifies rocks primarily into three categories: (1) the "Plutonites"—those of plutonic habit, (2) the Hypabyssal rocks and (3) the Extrusive rocks, and the criterion is supposed to be mode of occurrence. As a fact, however, the author states "gabbros . . . occur as stocks, sills and dykes." Now gabbro is a plutonite. Therefore it must have a plutonic mode of occurrence only; but sills and dykes are the most typical forms of hypabyssal intrusions. Thus, on Johanssen's own showing gabbro occurs sometimes in plutonic, sometimes in hypabyssal, rock-masses. But when he makes this admission, what criterion, apart from the obvious mineralogical definition, had he in mind? It can only be coarseness of grain. Gabbro is distinctive only in so far as its mineral composition and texture (grain-size) render it different from other rocks: mode of occurrence makes no contribution to this distinctiveness.

Again, the same writer admits that there is no reason why "dikes" or intruded sheets of basaltic composition should not be called "basalt dikes . . . for the mineral composition is exactly the same and there may be no difference in texture." In other words, as we have claimed, provided that the rock consists of the appropriate mineral assemblage and is sufficiently fine-grained, it is basalt whatever its mode of occurrence. Surely the logical conclusion must be that a national nomenclature cannot be based on mode of occurrence.

¹ *Descriptive Petrography of the Igneous Rocks*, vol. iii, p. 223.

² *Ibid.*, iii, p. 268.

(6) *Degree of Crystallization.*

These difficulties and uncertainties—for the mode of occurrence of a rock is, in many instances, uncertain—are overcome if the **degree of crystallization, or crystallinity**, is used instead as a basis of classification. Three degrees of crystallinity are distinguished, and are defined in terms of the average grain-size of selected components. The limits have been chosen so that in each compositional series most specimens from major (plutonic) intrusions fall in the "**coarse-grained**" category; most of those from minor (hypabyssal) intrusions fall in the "**medium**" group; while the majority of those with an extrusive mode of occurrence are classed as "**fine-grained**." By this careful choice of grain-size limits, a close correspondence may, in fact, be achieved between the three grain-size groups and mode of occurrence in the field. This tacit recognition of the importance of the latter as a controlling influence on cooling history, and therefore on texture, is lost if only two degrees of crystallinity are distinguished. This two-fold division is used in Shand's classification, in which the limit of unaided vision (aided by a simple lens for the myopic) is used to divide the well-crystalline (**Eucrystalline**) from the poorly crystalline (**Dyscrystalline**) rocks.

(7) *The "Clan" Concept in Classification.*

It has sometimes been urged that the rocks occurring as lava flows and minor intrusions should be dealt with separately from those of plutonic origin. The case for so doing rests on the belief that the conditions of formation are fundamentally different in the two cases. In particular, while the former are demonstrably magmatic, the magmatic origin of some of the latter is suspect. This is to a large extent a matter of the interpretation of certain lines of evidence; and until we are more familiar with ultimate origins, and understand more fully the true nature of magmas, it seems best to link together as members of the same **Clan**, all those rocks which are closely allied in composition, regardless of textural variation and even possible differences in origin. The term "clan" was introduced by R. A. Daly to include a series of rocks, essentially alike in composition, though covering the whole range of grain-size or other textural variation. The name applied to the Family in the coarse-grained group becomes the name of the Clan; thus amongst the chief ones are the Granite, Granodiorite, Syenite, Diorite and Gabbro Clans. The first two are separated from all the others by the essential rôle of quartz. In the Acid and the Intermediate Clans, the variation in the kinds and amounts of feldspars provide the chief means of discrimination; and although this is to some extent true of the basic rocks also, in the latter the ferromagnesian silicates play a more important part as they become quantitatively dominant.

CHAPTER II

THE ACID IGNEOUS ROCKS

THIS exceedingly important category comprises all those rocks covered by the term "igneous" as defined above (p. 23), which contain quartz as an essential constituent, to the extent of 10 per cent or more. All textural variations are included, from the ultra-coarse to the cryptocrystalline and glassy. In the absence of phenocrysts of quartz, the fine-grained and vitreous rocks can be judged on their content of normative (as distinct from modal) quartz.

After quartz, the most significant constituents as a rule are the feldspars, which are used to group the Acid Igneous Rocks into

Grain Size.	Alkali-Feldspar > $\frac{1}{2}$	Alkali-Feldspar and Plagioclase each between $\frac{1}{2}$ and $\frac{1}{3}$	Plagioclase > $\frac{1}{2}$
Coarse	ALKALI- GRANITES	ADAMELLITES	GRANODIO- RITES
Medium	ALKALI- MICROGRANITES	MICRO- ADAMELLITES	MICRO- GRANODIO- RITES
Fine	ALKALI- RHYOLITES	RHYO-DACITES OR TOSCANITES	DACITES

three Clans, according to the ratio of alkali-feldspar to plagioclase, excluding albite. In the initial stages of classification we group together as alkali-feldspar the potassic orthoclase, microcline and sanidine, with the sodic albite and the perthites. As alkali-feldspar and plagioclase may be present in all proportions, the subdivision must be made on an arbitrary basis. The chosen proportions are indicated in the appended table. The three clans so defined take the names of the coarse-grained members in each case.

The coarse-grained rocks of all three clans are conveniently grouped together as "granites." When the term "granite" is used without any qualifying adjective, it signifies a rock of the appropriate coarse texture, composed essentially of quartz, feldspar and mica. Similar wide terms covering all the acid rocks in the medium

and fine-grained categories are "microgranite" and "rhyolite" respectively. When it is desired to identify the rock more precisely, due consideration must be given to the kind (or kinds) of feldspar present, and it becomes possible to apply the more special terms shown in the table.

In the account which follows, we describe first the coarse-grained rocks in all three clans, then those of medium grain, and finally their fine-grained equivalents.

THE GRANITES

(1) THE ALKALI GRANITES

It is possible to effect further subdivision after study of the dominant alkali-feldspar: with orthoclase, microcline or sanidine in excess over albite, the rock is said to be potassic. Conversely, with albite in excess, the rock is sodic.

The Potassic Granites.

Apart from their allotted quota of quartz, dominant alkali-feldspar with or without subordinate plagioclase, potassic granites vary considerably in the kinds and amounts of coloured silicates present. Commonly the latter is biotite, often in close association with muscovite. This is consistent, of course, with the high content of potash (K_2O) and alumina (Al_2O_3) shown in the analyses of such types. Hornblende is not common in alkali-granites, while augite is unknown in these rocks. Orthopyroxene (hypersthene) does occur, however, in the curious and rather problematical type, charnockite, described more fully below. In the normal potassic granites quartz averages 25 per cent of the whole, and is notably subordinate in amount to the alkali-feldspar. The amount of coloured silicate is small: indeed, many granites of this type are **leucogranites**,¹ with a colour index of 5 or less. The relationship of the quartz to the feldspar varies in different specimens. It may be interstitial and bounded by the plane surfaces of surrounding feldspars; or it may be lobed into them in a manner suggesting a replacive relationship (Fig. 81). When microcline is present some of the quartz occurs as rounded grains embedded in the feldspar, but much of it is of later formation than the microcline. Finally, some quartz commonly

¹ A. Brammell has described facies of the Dartmoor granite from Wittenbarrow, in which feldspar (71 per cent) and quartz (26 per cent) make up 97 per cent of the whole rock: the colour index is only 3. A similar rock was named *alaskite* by Spurr (1900), while E. B. Bailey has used the word *aplogranite* for others in the same general category. In mineral composition these light-coloured granites resemble *aplites* (see p. 207); but they differ from the latter in texture and mode of occurrence, and a better name, conveying no implications of origin, is *leucogranite*.

ANALYSES OF ALKALI-GRANITES.

	I. Charnockite.	II. Sodic leucogranite, Mountsorrel.	III. Riebeckite- granite, Nigeria.	IV. Sodic granite, Rockall type.	V. Potassic leucogranite, Dartmoor.	VI. Potassic granite, Dartmoor.	VII. Potassic-sodic granite, Dartmoor.	VIII. Potassic granite, Lamorna.
SiO ₂	77.47	76.70	75.29	69.80	73.16	73.66	71.69	74.69
Al ₂ O ₃	11.00	12.58	13.33	5.10	13.95	13.81	14.03	16.21
Fe ₂ O ₃	1.04	0.10	0.52	13.23	0.03	0.21	0.57	tr.
FeO	2.02	2.09	1.40	0.78	0.47	1.51	1.93	1.16
MgO	0.43	0.65	0.22	0.11	tr.	0.45	0.66	0.48
CaO	1.02	1.10	0.64	0.72	0.43	0.67	1.49	0.28
Na ₂ O	2.86	4.90	3.80	8.04	2.57	2.89	3.03	1.18
K ₂ O	4.14	0.52	3.97	0.22	8.16	5.02	4.59	3.64
H ₂ O	0.25	0.85	0.70	0.77	0.64	1.66	1.76	1.23
TiO ₂	0.26	0.20	tr.	0.34	0.04	0.16	0.33	—
Rest	—	0.14	0.04	1.73	0.17	0.31	0.29	0.68
	100.59	99.83	99.91	100.84	99.62	100.35	100.37	99.55

I. Charnockite, Madras, India (Anal. H. S. Washington, *Amer. Journ. Sci.*, xli (1916), p. 323.
 II. Sodic leucogranite, marginal facies of Mountsorrel granodiorite, Charnwood Forest, Leicestershire (Anal. W. H. Herdsman), *Geol. Mag.*, 1934, p. 1.

III. Riebeckite-granite, Kudaru Hills, Nigeria (Anal. W. H. Herdsman), *Q. J. G. S.*, 1934, p. 222.

IV. Sodic granite, Rockall type (Washington), (Anal. H. S. Washington), *Q. J. G. S.*, lxx (1914), p. 297.

V. Potassic leucogranite ('aplogranite'), Wittabarrow, Dartmoor (Anal. H. F. Harwood), *Min. Mag.*, xx (1923), p. 41.

VI. Potassic granite, Haytor East Quarry, Dartmoor (Anal. H. F. Harwood, *op. cit.*).

VII. Potassi-sodic granite, Saddle Tor, Dartmoor (Anal. H. F. Harwood, *op. cit.*).

VIII. Potassic granite, Lamorna, Cornwall (W. Pollard).

occurs in these rocks in the form of "vermicules" embedded in plagioclase, forming the intergrowth known as myrmekite (Fig. 80). Many of the larger areas of quartz in thin sections of granites of all kinds are seen to be aggregates of grains, sutured together, and of random orientation.

The alkali-feldspar in these rocks may be orthoclase or microcline or microperthite, and as we have seen, may be associated with a sodic plagioclase, usually within the oligoclase range of composition.

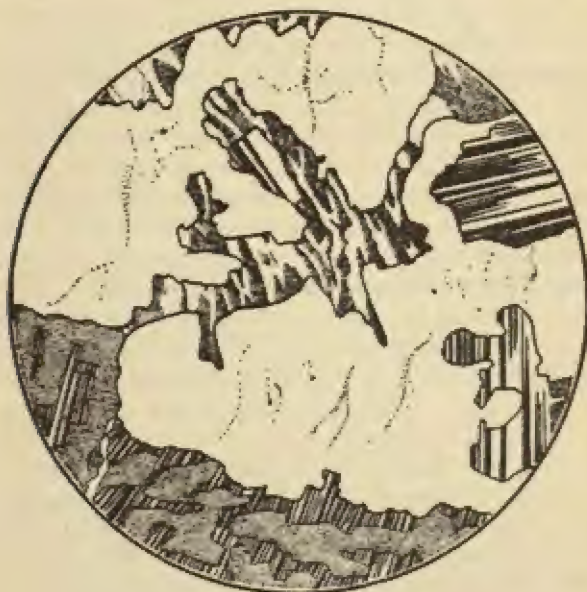


FIG. 81

Potassic leucogranite, Mt. Mado, Jersey, C.I.

(Reproduced by permission of the Council of the Geologists' Association.)

In many hand-specimens, the former is a shade of pink, while the latter is white; but there are grey granites in which either or both may be off-white. In thin section the two kinds of feldspar may usually be distinguished by differences in the degree of alteration (see, for example, Fig. 87); but in perfectly fresh specimens reliance may be placed on the differences in refractive indices, even when the more obvious differences in twinning fail. Again, there may be a marked difference in habit between the alkali-feldspar and the plagioclase, which becomes more important in the types richer in plagioclase, considered below. The feldspars in these alkali-granites seem particularly subject to alteration by deuteric or pneumatolytic

processes. Commonly small flecks of sericite in potassic, or paragonite in sodic feldspars appear, sometimes aligned parallel to the cleavages; while dense aggregates of kaolinite cloud the feldspar and may render it partially or even wholly opaque in thin section. In addition to the secondary white mica which replaces feldspar, primary muscovite may also occur, perfectly fresh on account of its chemical stability, and in close association with biotite, which is penetrated by, and wraps round the white mica. The biotite is a strongly pleochroic variety: it may vary from deep sepia or red-brown to straw yellow. It may show any degree of alteration into chlorite, which appears first along the cleavages, but may spread so as to pseudomorph the mica completely. Usually little can be seen of the accessory minerals in granites in thin sections, though many may be obtained by crushing and separation. However, the biotite may show pleochroic haloes, looking like ink-blots on the section, often in extraordinary numbers. In central sections through these, the cause of the halo—a minute zircon crystal—will be seen. Iron-ores are usually present, but only in small amount compared with almost every other type of igneous rock.

Examples of such alkali-granites are found among the Armorican masses of south-western England; but it must be noted that granites of extreme composition, whether potassic or sodic, are rare: most specimens are mixed—they are either sodi-potassic or potassi-sodic.

A distinctive type which falls in this category is **charnockite**, described originally from a locality in Madras.¹ The type rock contains quartz 40, microcline 48, oligoclase 6, hypersthene 3, biotite 1, and magnetite 2 per cent. In hand specimens the quartz appears bluish, while in thin section it is seen to be charged with extraordinary numbers of minute acicular crystals, identified as rutile, occurring in hundreds of thousands per cubic centimetre. Apart from this, the outstanding feature is the occurrence of distinctly pleochroic hypersthene. This links charnockite with a series of hypersthene-bearing rocks of varying composition—the charnockite series—known to occur in India and Uganda.²

The fundamental difference in the nature of the coloured mineral content between charnockite and a normal potassic granite reflects a difference in chemical composition. The presence of muscovite particularly, and of biotite in lesser degree, indicates a high content of K and Al, in excess of the requirements of the feldspars. Such

¹ Holland, T. H., "The Charnockite Series . . ." *Mem. Geol. Surv., India*, 1900, part 11, p. 162; and Rao B. Rama, *Bull. Mysore Geol. Dept.*, No. 18 (1945).

² Groves, A. W., "The Charnockite Series of Uganda" *Quar. Journ. Geol. Soc.*, xci (1935), p. 150.

rocks are termed *peraluminous* by Shand. By contrast charnockite is an example of a *subaluminous* type (Shand) for there is no excess Al or alkalis, and therefore no mica.

The Sodid Granites.

True sodic granites are rare, but when they do occur, are found to be very distinctive rocks, particularly as regards their coloured silicates. Instead of the micas, hornblende or orthopyroxene, these rocks contain a sodium-iron pyroxene, usually aegirine, often associated with one of the strongly coloured amphiboles of like composition. Of the latter riebeckite is the commonest. Both types of mineral are non-aluminous, but rich in alkali and iron. These rocks therefore stand in direct contrast to the peraluminous types, and are aptly termed *peralkaline* (Shand). Typical examples of these rocks occur in plutonic complexes in Nigeria, one of these forming the Kudaru Hills,¹ where the dominant type is a coarse-grained riebeckite-granite with the following composition: quartz 38, microperthitic feldspars 58 and riebeckite 4 per cent. Nearer to hand, peralkaline granites build the islet of Rockall² in the North Atlantic, the dominant type being one carrying both aegirine and riebeckite. A melanocratic facies has been called **rockallite**, in which the colour-index is very high for granitic rocks—39; the feldspar is albite, 23, while the quartz totals 38 per cent.

As defined above, sodic granites are not necessarily peralkaline: with rather more Al and less Fe, a type occurs which is no less strongly sodic, but is more ordinary in its coloured mineral content. In such rocks the whole of the Na is locked up in the feldspar, which, by definition, may be albite, but is commonly either microperthite, antiperthite, or cryptoperthite. These are the dominant components, associated, of course, with the requisite amount of quartz, with biotite and the usual accessories.

(2) THE ADAMELLITES

In this category are included those granitic rocks in which Ca-bearing plagioclase accompanies a potassic feldspar in approximately equal amounts: neither the potassic feldspar nor the plagioclase may exceed two-thirds of the total feldspar present. Thus, compared with the alkali-granites, adamellites are distinctive through the increasing importance of Ca-atoms in the feldspar. Generally the plagioclase lies within the oligoclase range, but may be andesine. The essential quartz, potassic feldspar and plagioclase are accom-

¹ Bain, A. D. N., "The Younger Intrusive Rocks of the Kudaru Hills, Nigeria," *Quar. Journ. Geol. Soc.*, xc (1934), p. 201.

² Tyrrell, G. W., "The Petrology of Rockall," *Geol. Mag.*, lxi (1924), p. 19.

panied by biotite in some adamellites, but by biotite and common hornblende in others. In the definition no limitation is placed upon the content of dark minerals; but as a rule the colour-index is rather higher than in alkali-granite, but lower than in granodiorites.

The name adamellite was originally suggested for a type now distinguished as tonalite, but was redefined by Brögger (1895) in substantially the sense in which we use it here. The type locality is the Adamello Complex in the Tyrol; but adamellite is a widely distributed type, though often referred to merely as biotite-granite or biotite-hornblende-granite. A well-known British example occurs at Shap Fell* in Westmorland. Part of the complex consists of a particularly handsome rock characterized by numbers of large pinkish phenocrysts of orthoclase, embedded in a granular aggregate of white oligoclase, quartz and biotite. Micrometric analysis[†] shows this adamellite to contain approximately quartz 24, orthoclase 36, oligoclase 34 and biotite 6 per cent.

It may be noted that the Intermediate equivalents of adamellites are monzonites, which differ chiefly in being quartz-free, or contain only subordinate amounts of this mineral. Some petrologists therefore use the term "quartz-monzonite" for adamellite.

(3) THE GRANODIORITES

Of all the coarse-grained granitic rocks, those which fall in this category are quantitatively the most important: indeed though only one division of the Acid igneous rocks, they are far more widespread than all the coarse-grained members of the Intermediate and Basic Clans combined. In existing records, however, care must be taken to see the exact sense in which the name is being used—usage is varied, and there is a good deal of confusion as between granodiorite, tonalite, quartz-mica diorite and adamellite. In all of these types plagioclase is a significant component; but it is of equal status with alkali-feldspar in adamellite, while it is dominant, to the extent of at least two-thirds of the total feldspar, in the other types named. While granodiorite is Acid, however, tonalite and quartz-mica diorite are of Intermediate composition: they contain quartz only as an *accessory*, not as an essential component.

Granodiorites, then, are coarse-grained igneous rocks containing essential quartz (more than 10 per cent), with plagioclase dominant, though alkali-feldspar may occur, but must not exceed one-third of the total feldspar content. These felsic minerals are accompanied by a varying proportion of coloured silicates and accessories, of which

* Grantham, D. R., "Petrology of the Shap Granite," *Proc. Geol. Assoc.*, xxxix (1928), p. 299.

† Holmes, A., *Petrographic Methods and Calculations*, 1921, pp. 594-9.

biotite and hornblende are almost constantly present in the former, and sphene, apatite and magnetite in the latter category.

This is almost exactly the original sense in which the name was first used (Becker, 1892, in conjunction with H. W. Turner¹ and W. Lindgren²) as applied to certain rocks of the Sierra Nevada range. Thus defined, granodiorite transgresses the silica-percentage boundary formerly used to separate the Acid from the Intermediate igneous rocks. There are as many granodiorites with less than 66 per cent, as there are with more than this amount of total silica. The centre point of the family would average 66 to 67 per cent total silica, and of this about 22 per cent is quartz. There is a perfect gradation into tonalite, which differs only in the subordination of quartz.

Granodiorites in which alkali-feldspar is completely (or almost completely) suppressed, have been termed **trondhjemites** (Goldschmidt, 1916), and consist of plagioclase of the appropriate range of composition for granodioritic rocks—oligoclase to andesine—together with quartz and small quantities of biotite, sometimes proxied by hornblende or pyroxene. With an average SiO_2 percentage of over 70, and 20 to 30 per cent of quartz, it is appropriate to include them in this category, but there is little justification for disguising them under this generic name: they are merely orthoclase-free granodiorites, and in mineral composition are very close to quartz-rich tonalites.

Many loosely named "hornblende-biotite granites" are granodiorites. As an example we may quote the Mountsorrel intrusion from Charnwood Forest, Leicestershire.³ The major part of this intrusion is granodiorite containing, on average, quartz 22.6, alkali-feldspar 19.7, plagioclase 46.8, biotite 5.8, hornblende 2.9, and magnetite 2.2 per cent. Similar types occur also among the Caledonian and Devonian granitic complexes of the Highlands and Southern Uplands of Scotland, as in the Moor of Rannoch and Ben Cruachan complexes. The average composition of the recently-described granodiorites from the Garabal Hill-Glen Fyne complex⁴ is all but identical with the Mountsorrel rock quoted above, but there are striking textural differences: the Scottish type includes strongly porphyritic varieties, in which the phenocrysts consist of alkali-feldspar (microcline-microperthite) while plagioclase forms

¹ "The Rocks of the Sierra Nevada," 14th Ann. Rep. U.S. Geol. Surv., 1894, pp. 478 and 482.

² Amer. Journ. Sci., 1897, p. 269.

³ Richardson, A. W., "A Micrometric Analysis of the St. Austell Granite," Quar. Journ. Geol. Soc., lxxix (1923), p. 554.

⁴ Nockolds, S. R., "The Garabal Hill-Glen Fyne Igneous Complex," Quar. Journ. Geol. Soc., xcvi (1940), p. 451.

ANALYSES OF ADAMELLITES AND GRANODIORITES

	I. Adamellite, Abriachan.	II. Adamellite, Rubislaw.	III. Adamellite, Shap Fell.	IV. Adamellite, Aberlour.	V. Trondhjemite Average.	VI. Average Granite- Diorite.	VII. Granodiorite, Moor of Rannoch.	VIII. Granodiorite, Moor of Nevada City.
SiO ₂	71.25	69.01	68.88	68.01	70.27	64.17	66.91	66.65
Al ₂ O ₃	18.03	17.74	14.17	17.34	16.01	15.74	15.09	16.15
Fe ₂ O ₃	1.29	0.97	0.87	3.66	0.89	2.39	1.70	1.52
FeO	0.34	2.05	1.66	—	1.33	3.12	2.13	2.36
MgO	0.38	0.48	1.33	0.77	0.77	2.56	2.02	1.74
CaO	2.61	1.95	2.32	2.06	2.98	4.42	3.32	4.53
Na ₂ O	2.25	2.73	3.30	2.05	5.31	3.48	4.16	3.40
K ₂ O	3.09	3.94	5.06	4.41	1.53	3.15	3.16	2.65
H ₂ O	0.82	1.18	1.25	0.64	0.55	—	0.70	0.90
TiO ₂	—	—	0.62	0.83	0.22	0.62	0.67	0.38
Other constituents	0.13	—	0.51	0.48	0.14	0.35	0.17	0.29
	100.19	100.05	99.97	100.25	100.00	100.00	100.03	100.57

I. Adamellite, Abriachan, Loch Ness, Scotland (W. Mackie).

II. Do. Rubislaw, Scotland (W. Mackie).

III. Do. (Stage II Granite). Shap Fell, Cumberland (Anal. H. F. Harwood), *Proc. Geol. Assoc.*, 1928, p. 311.

IV. Do. Ruthrie Granite, Aberlour, near Ben Rinnes, Strathspey.

V. Trondhjemite, average of five analyses quoted by Johannsen, 1933, p. 385.

VI. Daly's mean between average granite and average diorite.

VII. Granodiorite, Moor of Rannoch, Scotland (Anal. E. G. Radley).

VIII. Do. Nevada City, California (W. Lindgren).

subhedral grains, usually zoned, and associated with the quartz, hornblende, mica and prominent pale brown sphene.

THE TEXTURES OF GRANITES

The term "granitic" used in a textural sense implies no more than that the rock concerned is granular, *i.e.*, like a granite. Typically, none of the major constituents is bounded by crystal faces: their shapes have been determined by mutual interference during growth. This most typical of the wide range of granitic textures is sometimes termed "xenomorphic granular." It sometimes happens that the feldspars tend to exhibit crystal faces, though the quartz is again shapeless. For this variant, the term "hypidiomorphic granular" may be used.

The handsomest granites are undoubtedly the **porphyritic** types in which phenocrysts of white, grey or red feldspar occur embedded in a groundmass that may be identical in texture with an ordinary aphyric granite. The phenocrysts may be strongly zoned, and attain in some cases among the West of England granites to 7 in. by 5 in., measured on the side-pinacoid faces. They frequently lie in parallel orientation and thus provide significant data in structural studies of granitic rock-bodies. Instances of such granites have already been mentioned in the foregoing account. In Britain the Shap adamellite and the porphyritic variety of the Garabal Hill-Glen Fyne granodiorite are good examples; but the most striking specimens are obtained from the "giant granite" from Dartmoor.

The great majority of granites may be referred to one or other of these two main textural types. There remain for consideration certain varieties which call for more detailed consideration. **Orbicular granites**¹ consist of "orbs" of various sizes—they may measure several inches in diameter—embedded in a matrix of normal granitic texture. The "orbs" are, in fact, variously shaped, and far more distinctive than their shapes is the extraordinary rhythmic banding which they exhibit (Fig. 82). Each of these bodies contains a core which in some instances is of the same composition as the matrix in which they are embedded, but in other cases it is completely different. Again, although the texture of the matrix is sometimes normal granitic, it may show a continuation of the successional crystallization of the component minerals, in the sense that the interspaces between the orbs are filled largely with feldspar, but with mica (biotite) in the centre, representing the last mineral to

¹ Johanssen, A., *Descriptive Petrography of the Igneous Rocks*, vol. iii, p. 248. See particularly the photographs of a range of different types of orbicular granites.

crystallize. Most specimens so far described occur in Finland,¹ and some of them are objects of outstanding petrological interest. Much has been written concerning the significance of orbicular structure. Nuclei appear to be essential, and may be either xenoliths of wall-rock or cognate xenoliths of granite, *i.e.*, material of early consoli-

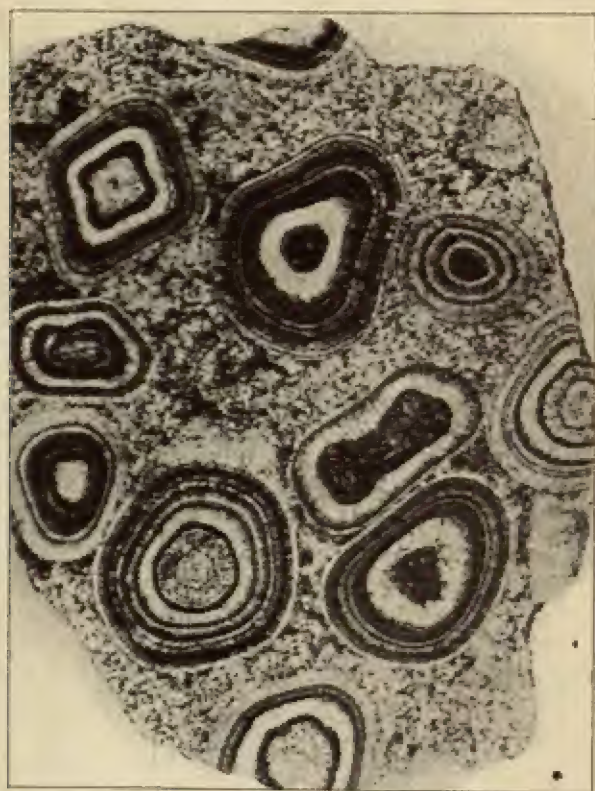


FIG. 82

Orbicular granite, Kangasala, Finland. $\times \frac{1}{2}$

Photo by A. V. Weatherhead.

dation broken up by, and incorporated in, later granitic magma. The magma may have been highly viscous, and diffusion consequently slow. This would favour successional rhythmic crystallization around the nuclei.

The rapakivi texture also was originally described from Finnish

¹ See Sederholm, J. J., "On Orbicular Granites . . .," *Bull. Com. Géol. Finlande*, No. 83, 1928.

granites. In typical specimens large flesh-coloured potassic feldspars occur as rounded crystals a few centimeters in diameter, and are mantled with white sodic plagioclase. These feldspars are embedded in a matrix of normal texture, but consisting chiefly of quartz and coloured minerals. Recently the term "rapakivi" has been applied to granites and even granite-porphyrries which contain phenocrysts of reddish orthoclase with narrow mantles of whitish sodic feldspar, for example, some facies of the Shap, Dartmoor and Jersey granites and associated minor intrusions. It is customary in these days to regard phenocrysts with suspicion—the possibility that they originated elsewhere than in the magma represented by the matrix in which they are now embedded, must be given due consideration. With the genuine Finnish rapakivi granites this may well have been the case, for the rounded form of the "phenocrysts" suggests magmatic corrosion. This would contribute material for a second generation of orthoclase, but if the magma were saturated with the components of albite, it would naturally be deposited upon the rounded remnants of the phenocrysts, forming the characteristic white rim.

The **graphic** or **runic texture** is one of the most distinctive shown by granitic rocks, and is particularly characteristic of the pegmatitic facies. Both terms have reference to the marked resemblance of the small quartz "hieroglyphs" to Runic characters, which show up clearly against the background of microcline in which they are embedded (Fig. 83). This texture is considered more fully under the heading "pegmatites" below.

Finally, some granites contain small irregular cavities lined with well-terminated crystals of the normal constituents of the rock, accompanied by some of the rarer accessories. Such granites are said to be **miarolitic**. In Britain the granites of the Mourne Mountains, in Ireland and Lundy Island off the Somerset coast provide typical specimens. Smoky quartzes, well-terminated feldspars, "books" of white mica, as well as rarer apatite and topaz crystals occur in the manner described. Again there is a link with pegmatites, for the most likely cause of the phenomenon is the existence in the magma of "pockets" of gas which included the fluorine sealed up in the white mica, topaz and apatite (see p. 202).

GRANITE-PEGMATITES AND APLITES

The rocks we have studied so far represent the major portion of the granite magma: the final residuum of large intrusions is naturally rich in the fugitive constituents of the magma, and by the freezing of this residuum, rocks are produced which differ markedly in both mineral composition and texture from the normal granite. In texture they fall into two contrasted types: the first of relatively coarse

grain; the second relatively fine. The former are the granite-pegmatites, and the latter granite-aplites.

Granite Pegmatites.

Few rocks are so well endowed with the power of capturing the imagination as the pegmatites. They are extremely coarse-grained and contain not only the world's largest crystals, but also the choicest mineral specimens. Further, the pegmatites are of considerable economic importance, since they are formed by the crystal-

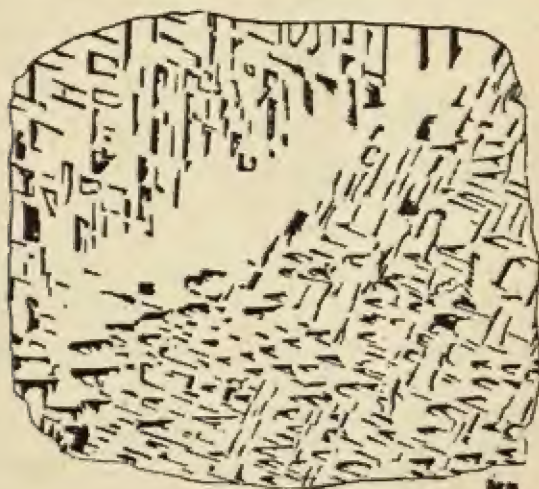


FIG. 83

Sketch of hand specimen of runite (graphic granite). Microcline plain; quartz hieroglyphs in black, showing shapes controlled by three directions in the host-mineral. *Natural size.*

lization of residual solutions in which there is often a marked concentration of rare elements.

The place that the pegmatite fluids hold in the cooling history of a granite mass, has already been mentioned (p. 164). That the main part of the crystallization is completed before the formation of the pegmatitic residuum is obvious from the relationship between pegmatitic bodies and the main granite masses with which they are associated. Most pegmatites occur in the form of irregular segregations, veins or small dykes or sills, which are especially abundant in the marginal parts of the parent granite, or in the country rock surrounding it, though some pegmatite veins occur at a distance from the main intrusion, and appear to have no visible connection with it.¹

¹ Anderson, Olaf, "Discussion of Certain Phases of the Genesis of Pegmatite," *Norsk. Geol. Tidsskr.*, vol. xii (1931), p. 1.

Pegmatite dykes do not, however, form an invariable part of all exposed granite masses: for although most of the latter contain occasional ultra-coarse-grained schlieren or clots, some are associated with a profusion of pegmatitic veins and dykes. The Precambrian granites seem particularly well endowed in this respect; but pegmatites are very poorly represented in association with many granites of later periods, for example, the great granitic batholiths of the Andes. In many instances the pegmatite dykes run conformably with the strike of the country rock, and in such abundance as to simulate a dyke-swarm.¹ Pegmatites are characteristic of regions of compression, not of tension, as is the case with true dykes. Further, unlike true dykes, the pegmatites are normally quite short, irregular in form, and rarely parallel-sided. The extent to which pegmatites are formed by *in situ* replacement remains an open question.

Mineral Composition.

Alkali-feldspar is the dominant constituent of all granitic pegmatites. In those classified as **simple pegmatites** it is generally microcline-micropertthite, associated with quartz and white mica. Among the abundant and varied accessory minerals are those normally occurring in granite, together with others which are often regarded as "pneumatolytic," such as tourmaline, topaz, the fluorine-bearing minerals and various ores.

Less commonly pegmatites consist of a much more varied mineral assemblage. In these **complex pegmatites** albite, or clevelandite, is an important constituent, often exceeding microcline in amount, and is accompanied by a suite of lithium-bearing minerals including red and green parti-coloured tourmalines, spodumene and lithiamicas such as lepidomelane, lithionite, etc. The special interest attaching to the complex pegmatites is discussed below, under the heading "paragenesis."

Textural Features.

One of the most characteristic features of granite-pegmatites is the development of the graphic or runic texture, resulting from the close intergrowth of feldspar—generally microcline-micropertthite and quartz. It was to this structure that Haüy originally applied the term "pegmatite," although in later years this has given place to "graphic granite" or "runite."²

Graphic granite presents many striking features and as many

¹ See, for example, the account given by T. W. Gevers and H. T. Frommurze, "The Tin-bearing Pegmatites of the Erongo Area, S.W. Africa," *Trans. Geol. Soc. S. Africa*, xxxii (1929), p. 111.

² Haüy's original term has survived, however, in "micropegmatite," which is a comparable structure, though on a finer scale, seen in the interstitial quartz-feldspar intergrowth in certain quartz-gabbros and quartz-dolerites.

problems. In the most regular examples the quartz takes the form of sub-parallel, elongated prisms which pass through the feldspar, and present the characteristic hexagonal cross-sections, often flattened and distorted in the manner of ordinary quartz crystals, of course. Fersmann has shown that the vertical axes of the quartz crystals are so inclined as to make an angle of approximately 70° with the vertical axis of the host feldspar. However, other investigators have been unable to confirm this regularity suggested by "Fersmann's Law." Apart from their attitude, it has been found that the proportion of quartz to feldspar is fairly constant, at about 30 to 70 per cent. These various features strongly suggest that the structure results from the crystallization of a eutectic or cotectic mixture of the two components. Despite this, however, origin by replacement of the feldspar by quartz has been urged by certain American authors.¹

The most striking textural feature of pegmatites is their extraordinary coarseness of grain. Impressive examples are afforded by a beryl crystal 19 feet, and a spodumene 47 feet long, associated with microcline-perthites several feet through, discovered in a pegmatite at Keystone, in the Black Hills, South Dakota. The growth of such large crystals must result primarily from the very low viscosity of the pegmatitic fluid, caused by the presence in it of abundant fluorine, magmatic water and other substances of low atomic and molecular weights. T. Quirke and H. Kremers² have suggested that the movement of fluid of constantly varying concentration and temperature through the interstices of the crystallizing pegmatite may be an important contributory factor in building up large crystals: a constantly replenished mother liquor could, in this way, largely surround each growing crystal. Occasionally, however, details of crystallization indicate that once a pegmatitic residuum has accumulated, it has remained static until crystallization has been completed. The Cornish pegmatite illustrated in Fig. 84 shows the growth of crystals, including thin acicular tourmalines, perpendicular to the roof of the sill-like intrusion from which the specimen was collected, and it is difficult to imagine the growth of such crystals in anything other than an undisturbed medium.

The *paragenesis* or order of crystallization of the several constituents has been worked out in full detail for a large number of pegmatites. It is usually found that intergrown quartz and alkali-feldspar (graphic granite) heads the list. The subsequent course of mineral deposition appears to be controlled by the gradual passage

¹ Schaller, W., "Mineral Replacements in Pegmatites," *Amer. Min.*, xii (1927), p. 59; also Wahlstrom, E., "Graphic Granite," *Amer. Min.*, xxiv (1939), p. 681.

² "Pegmatite Crystallization," *Amer. Min.*, xxviii (1943), p. 571.

of solutions of varying composition through the "pegmatitic thoroughfare." These from time to time are liable to effect changes in composition and textural relationships between the original com-

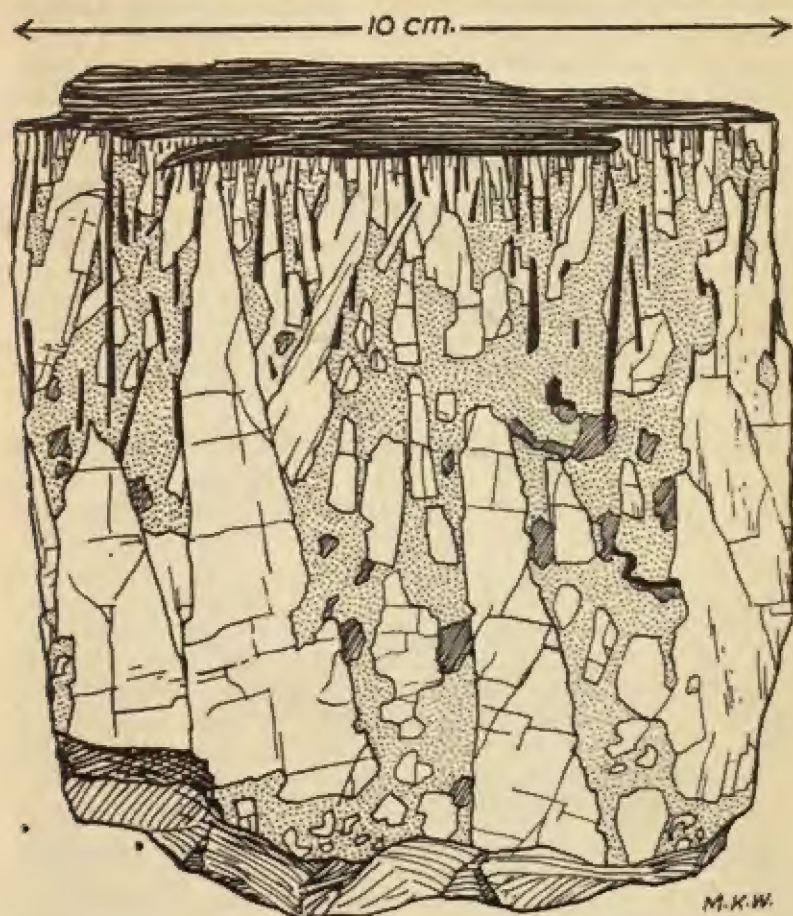


FIG. 84

Diagram of block of granite pegmatite showing the arrangement of crystals developed perpendicular to the roof of the sill, Porthleven, Cornwall. Tourmaline crystals, black; mica, shaded; quartz, stippled; and perthite, blank. Roof rock is tourmalinized shale.

ponents. In this way the albite (cleveandjite) of the complex pegmatites is produced at the expense of the earlier microcline-microperthite.¹ Striking replacement textures between these two minerals

¹ Schaller, W., "The Genesis of Lithium Pegmatites," *Amer. Journ. Sci.*, x (1925), p. 269.

are so frequently observed that the mechanism of this type of albitization is beyond question.

When the migrating solutions dissolve previously formed minerals faster than they deposit new ones, open cavities or vugs may result. These are often lined with fine crystals of smoky quartz, adularia, clevelandite, etc., and with hydrothermal incrustations. The quartz crystals in these cavities are in some cases continuous with the

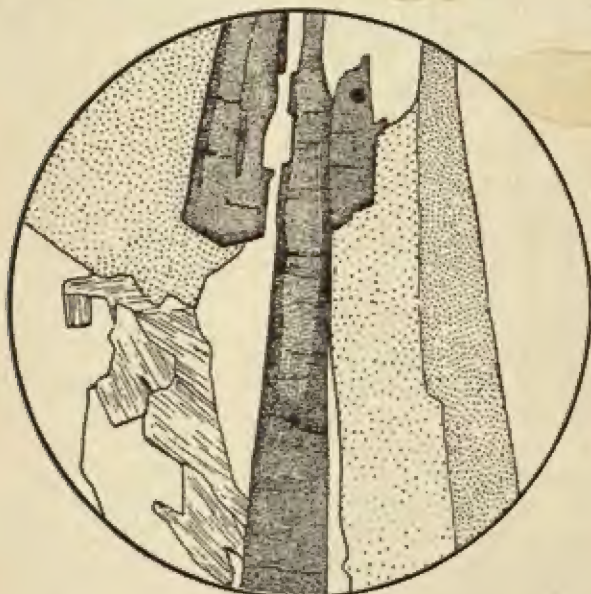


FIG. 85

Granite-pegmatite from pegmatite-aplite sill, an off-shoot of the Godolphin granite, Porthleven, Cornwall.

From the upper part of the specimen shown in Fig. 84.

Zoned tourmalines (heavy stipple); orthoclase (light stipple); feldspar (lined); quartz (blank).

quartz rods in surrounding graphic granite. The quartz crystals which grew freely into the cavities are of the alpha-type, while the intergrown rods show signs of having inverted from the beta-quartz type. In other words, during the growth of the quartz rods towards the vugs, the temperature fell below the inversion point at which high- is converted into low-temperature quartz: *i.e.*, at about 575°C . Thus for once we can make use of a reasonably accurate point on a geological thermometer, and state that pegmatite containing graphic granite normally commences to crystallize not far above 575° , say at 600° , C.

Granite-aplites.

These rocks occur as veins, as a rule, only a few inches thick, and although most abundant in the parent granite itself, they sometimes penetrate beyond its boundaries into the adjacent rocks. They are found in association with mica-lamprophyres (as rich in mafic minerals as aplites are poor), to which they are *complementary* in Brögger's sense. Chemically they are characterized by a high silica content and a considerable proportion of alkalis, with iron and magnesia in subordination. To this they owe their light colour—white to buff. In the hand-specimens they present a remarkably even and fine-grained saccharoidal texture, which, under the microscope, is seen to be microgranitic or micrographic. The dominant constituent is usually feldspar—a potassic, sodic or lime-bearing variety, according to the type of granite with which the aplites are associated. The proportion of quartz varies, but in some varieties this mineral predominates, indicating a passage to quartz veins.

Relation of Aplite to Pegmatite.

Aplites and pegmatites both occur as veins, dykes or sills in granites or the nearby country rock. Further, both types may be seen in the closest association in composite intrusions which may be pegmatitic in their marginal parts, but aplitic in the centre. Occasionally the two may be interbanded; or a vein dominantly aplitic may contain irregular pockets of pegmatite. This intimate association demonstrates that both rock-types represent granitic residua and that both have been generated in essentially the same way. There has been much speculation as to the cause of the striking difference in grain-size between these two residua. Probably aplites represent a "dry" and poorly fluxed fraction of the residual granitic magma, while the fugitive constituents were concentrated in the pegmatitic fraction. Doubtless the latter would be far more mobile than the former. The truth of this supposition is established at Porthleven, Cornwall, where pegmatite occurs in contact with the *under-side* of sedimentary xenoliths suspended in granitic (largely aplitic) sills. Such local pegmatite has obviously originated by the arrest of the upward-streaming volatiles.

There is no doubt that many pegmatites and aplites have originated in the manner outlined above; but in some cases a metasomatic origin is indicated by the field-relations of the rocks. If it is conceded that some granitic-looking rocks have originated by replacement, there are even stronger grounds for believing that the same is true of some pegmatites.²

² See King, B. C., *Journ. Geol.*, xlv (1948), p. 459.

PNEUMATOLYSIS

Following the final consolidation of the magma, the fugitive constituents are released, and escaping through joints and other fissures may effect striking changes in the mineral composition of the parent rock. These effects are covered by the term pneumatolysis, which implies that the fugitives are in a gaseous state. This is probably true in some cases, but not in others. Whether they exist as a true gas phase or not, however, they behave essentially as chemically active solutions. Pneumatolytic modifications are most strikingly displayed by granitic rocks (though they are not restricted to the latter), and include (a) greisenizing and (b) tourmalinization. Kaolinization is sometimes included, but is better regarded as hydrothermal alteration.

(a) **Greisenizing.**—Greisen, composed essentially of white mica and quartz, is one of the most distinctive products of this type of activity, and appears to have three different modes of occurrence, depending upon the degree of consolidation and fissuring of the parent rock.

(1) Most commonly greisen is a marginal modification of granite adjacent to quartz- and mineral-veins. The alteration is very localized: normally it extends for a distance of a few inches only from the contact. Usually there is convincing evidence of replacement, such as the pseudomorphing of feldspar crystals by aggregates of white mica. The latter is often a variety containing lithium and fluorine, such as zinnwaldite. Other fluorine-bearing minerals, notably fluorite and topaz, are also commonly present. Purple patches of fluorite give colour to an otherwise light grey or white rock. Topaz is an almost constant accessory, and in some specimens becomes an important constituent, even exceeding the white mica in amount. The end-product of this line of variation is a topaz-quartz rock, the former making up perhaps nine-tenths of the rock, to which the name "topazfels" is commonly, though incorrectly, applied. Granites vary widely in the extent to which they display pneumatolytic effects, and this type of greisenizing is developed extensively in only a few areas, such as the tin-mining districts in the Erzgebirge in Saxony and in Cornwall.

(2) In other occurrences the volatile-rich residuum does not alter the parent granite, but gives rise to veins and thin dykes of white-mica, quartz rock which crystallizes in fissures in the granite. Such occurrences are fundamentally different in nature and origin from the demonstrably metasomatic greisens noted above. They are just as definitely primary igneous rocks as aplites and pegmatites. Thus if the name "greisen" implies a metasomatic origin as well as a

particular mineral assemblage, another name is needed for these rocks. Spurr¹ has suggested the name "esmeraldite" for primary quartz, white-mica rocks. A better alternative is to apply the term "greisen" to all such rocks, and to indicate the mode of origin by appropriate qualifiers.

(3) Large bodies of greisen sometimes occur as apophyses and marginal facies of granite masses. They are not related to jointing or fissuring in any way, and are obviously different from the greisens considered under (1) and (2) above. A typical example is afforded by the outcrop at Grainsgill, just north of the main part of the Skiddaw granite, Cumberland. The chemical gains and losses of the greisen as compared with the main granite are different in this case from those which usually apply.² There is usually a considerable increase in H_2O , F and probably Al, while Na may decrease to zero. Other components may show small but haphazard changes. When the analyses of Skiddaw granite and Grainsgill greisen are compared, there is found to be an increase in SiO_2 in the latter, which is too great to be accounted for by hydrothermal alteration.³ A. Harker⁴ suggested that the greisen crystallized from a particularly acid magma-fraction which was separated from the main granite and driven northwards by filter-press action. As the greisen yields evidence of replacement of the original feldspars, however, it is probable that two processes have been involved: firstly, differentiation on the lines suggested by Harker, and secondly, deuteric alteration by an active residuum. Retention of the late-stage solutions in such large volumes must depend on such geological "accidents" as the shape of the differentiated body—ideally an apophysis of the main mass—and the degree of fissuring of the surrounding rocks, which must affect the escape of the volatiles.

This three-fold division of greisens and greisen-like rocks into (1) primary, (2) metasomatic and probably pneumatolytic and (3) deuteric, is paralleled among granites affected by tourmalinization.

(b) **Tourmalinization.**—Tourmaline, like muscovite, appears as a normal constituent of some granites of the more acid and alkali-rich types, as in the Carnmenellis mass in Cornwall. A particular concentration of boron produces a brown iron-rich tourmaline in place

¹ "The S. Klondyke District, Esmeralda County, Nevada," *Econ. Geol.*, i (1906), p. 382.

² A valuable summary of the gains and losses involved in greisenizing is given by G. J. Williams: "A Granite-schist Contact in Stewart Island, New Zealand," *Quar. Journ. Geol. Soc.*, xc (1934), p. 348.

³ Hitchen, C. S., "The Skiddaw Granite and its Residual Products," *Quar. Journ. Geol. Soc.*, xc (1934), p. 158.

⁴ "Carrock Fell granophyre and Grainsgill greisen," *Quar. Journ. Geol. Soc.*, li (1895), p. 143.

of biotite, so that the two minerals are very seldom seen together. With increasing flux-concentration tourmaline increases at the expense of other constituents of the granite; in particular, the feldspar is progressively eliminated. **Luxullianite**¹ represents an arrested stage of tourmalinization, in which some brick-red feldspar has survived, though the outlines of the crystals are much corroded. Between them quartz and finely acicular black tourmaline are much in evidence (Fig. 86).

Under the microscope luxullianite is a beautiful rock. The black tourmaline (schorl) occurs in the form of delicate needle-like crystals radially disposed and often clustered around corroded relics of earlier "massive" brown tourmaline. The tourmaline needles freely penetrate into secondary quartz, a mosaic of which forms the general background of the sections. The feldspars have been deeply embayed and show progressive replacement chiefly by quartz.

A second stage of tourmalinization is represented by rare tourmaline-quartz rocks in which none of the original components save quartz has survived; but although completely replaced, the shapes of the feldspars can still be detected, though their substance is chiefly quartz-mosaic.

In other instances tourmaline occurs in imperfect stouter prisms of random orientation, embedded in coarse quartz mosaic, giving a black-and-white rock of distinctive appearance. A well known example of this type is that of Roche Rock, Cornwall, which forms an isolated outcrop with no visible connection with the nearby main granite intrusion. There is, indeed, no evidence, microscopic or otherwise, that this rock ever was a normal granite: it may well represent a magma-fraction drastically enriched in "fugitives" and analogous with the "primary greisen" noted above. Apart from such occurrences, however, the same mineral assemblage, sometimes with cassiterite in addition, occurs in the form of primary veins.

Finally, it may be noted that the activities of the fugitive constituents are not limited by the boundaries of the parent granite, for the surrounding rocks are sometimes extensively altered.

(c) **Kaolinization.**—The partial alteration of feldspars into an exceedingly fine aggregate of flaky minerals of the kaolinite type is a ubiquitous phenomenon in granitic rocks. Such kaolinite is usually accompanied by sericite, and together these two minerals are the chief cause of the opacity of orthoclase in the hand specimen and its cloudiness in thin section. Occasionally kaolinization is so complete that the whole rock is reduced to a thoroughly rotted

¹ Wells, M. K., "A contribution to the Study of Luxullianite," *Min. Mag.*, xxvii (1946), p. 186.

² "Handbook to the Collection of Kaolin, etc.," *Mem. Geol. Surv.*, 1914.

condition, becoming friable and so soft that the rock can be easily dug away, or even removed by a high pressure jet of water. In this condition the rock is of great economic importance as **china clay**,

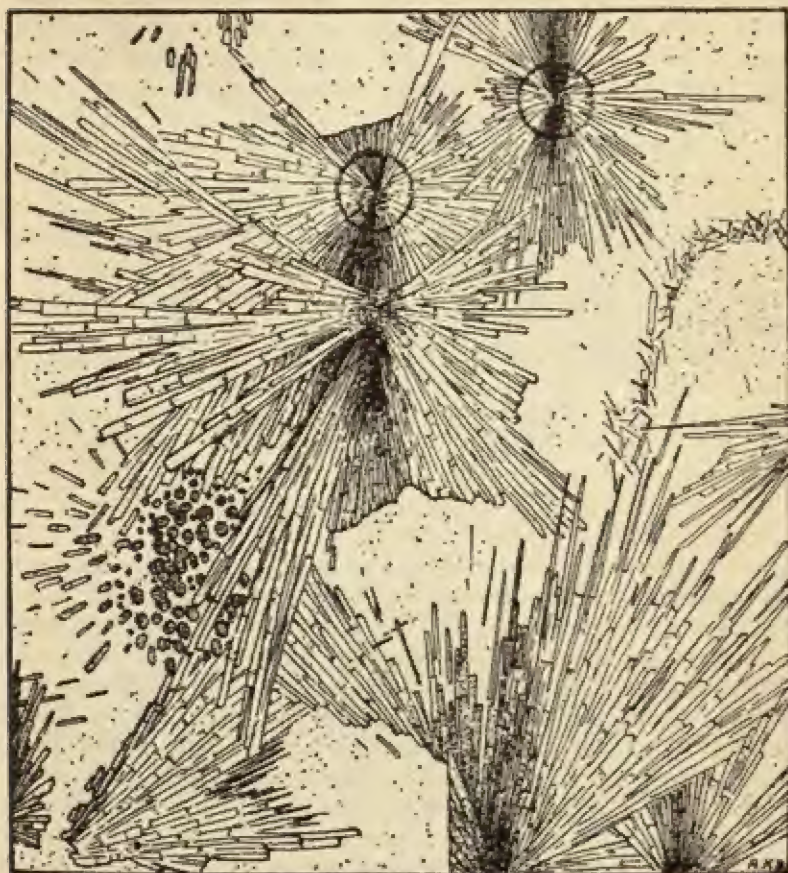


FIG. 86

Section of luxullianite (the type-rock), Luxullyan, Cornwall.

Tourmaline in radial aggregates; quartz of two periods, some pre-tourmaline, some secondary after feldspar. The boundary of a crystal of the latter, completely silicified, is outlined with acicular tourmaline on right, near top of section. Longest tourmaline crystals are 2 mm.

perhaps the most valuable raw material in the ceramic industry. Of the original minerals of the granite, only the quartz survives kaolinization. Large masses of the St. Austell granite in Cornwall have been modified in this way, giving china clay in association with other late-stage alteration products such as quartz-tourmaline rock and

china stone. The latter rock is comparable with luxullianite in a sense, as it represents an arrested stage of alteration—this time of kaolinization—and exhibits a wide variety of replacement textures. Two feldspars are present: strongly kaolinized orthoclase, often micropertthitic, and relatively fresh euhedral albite. The orthoclase may be extensively veined by secondary quartz and by fluorite. The latter is an essential component in more than the usual petrographical sense, for it gives the rock its fluxing properties in the glazing of china. It occurs in a variety of forms, either replacing feldspar or penetrating along the cleavage planes of muscovite as shown in Fig. 87.

The chief agent of kaolinization is probably high-temperature H_2O which attacks the orthoclase ($KAlSi_3O_8$) etc., to form kaolinite, $Al_2Si_2O_5(OH)_4$, and releases a certain amount of potassium which may combine with CO_2 to form a carbonate and thus be removed as a soluble component; or the potassium may combine with other components to form sericite which is so commonly associated with the kaolinite. Carbon-dioxide may thus play a part in these reactions, but it is uncertain how important a part.

THE MICROGRANITES

Under this omnibus title are grouped the medium-grained equivalents of the granites, including the alkali-granites, adamellites and granodiorites. "Medium-grained" in this sense comprises all those rocks with average grain-size lying between the limits of 1 mm. and 0.05 mm. The British Association Committee on Petrographic Nomenclature,¹ after considerable discussion where to draw the line between coarse-grained granites on the one hand and medium-grained microgranites on the other, chose an average grain diameter of 0.5 mm. In the present writers' opinion this limit is too low. The only outside criticism of the grain-size principle in rock classification has also been directed against this choice, and in the circumstances the writers feel justified in raising it to 1 mm., thus bringing the Acid into line with the Basic rocks. The advantage of having a uniform grain-size limit between "coarse" and "medium" seems to outweigh the sole disadvantage—that certain rocks formerly called granites now become microgranites under this scheme. The limiting grain sizes are the diameters of the majority of equidimensional grains of quartz and feldspar, ignoring phenocrysts. For general purposes it is sufficiently accurate to define microgranites as rocks of granitic composition and grain size ranging from 1 mm. down to the limit of unaided vision. With further diminution of grain size these rocks grade into rhyolites.

¹ Report by the Secretary (A.K.W.) in *Geol. Mag.*, 1936, p. 323.

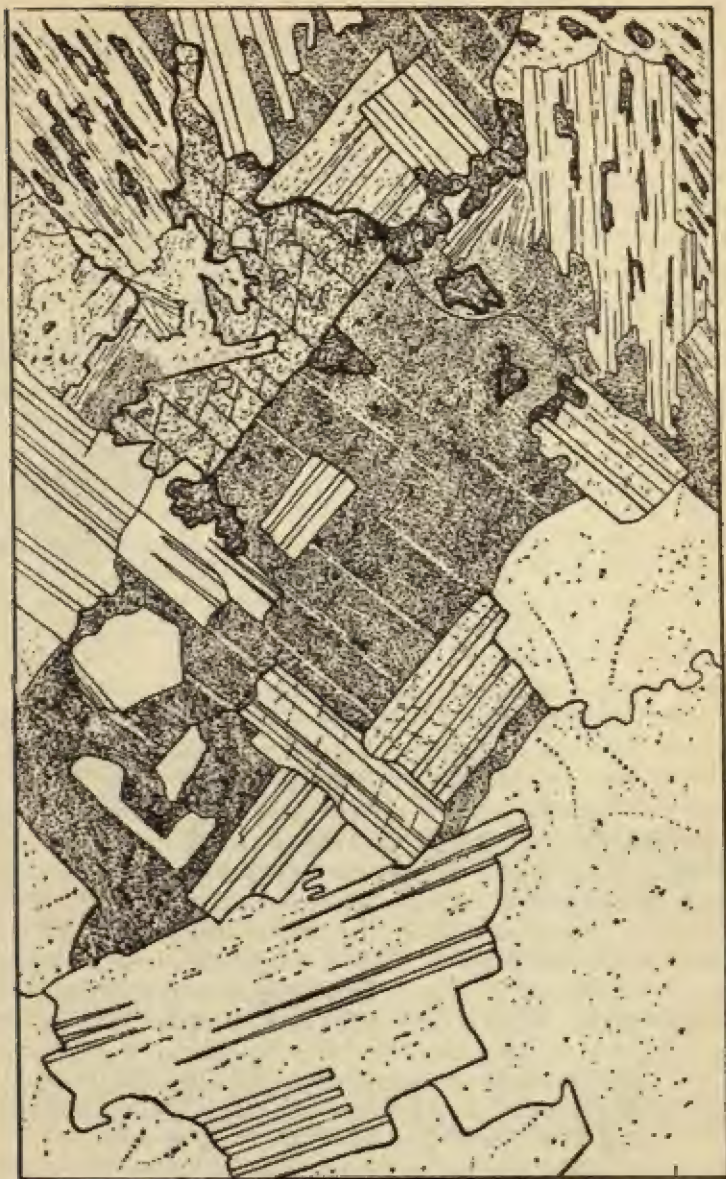


FIG. 87

A.K.W.

Cornish "China stone." Orthoclase (stippled) is strongly kaolinized, while albite is relatively fresh. Quartz contains numerous inclusions. Fluorite is conspicuous in muscovite, and in larger, colourless interstitial patches, showing octahedral cleavage. One topaz crystal in the top left of the section.

According to the details of their mineral composition the following may theoretically be distinguished:—

alkali-microgranites, microadamellites and microgranodiorites.

The means of distinction lies in the ratio of alkali- to plagioclase feldspar, as for their coarse-grained equivalents; but as we have seen, the distinction is sometimes difficult even when dealing with the latter. With these finer-grained rocks the difficulties are accentuated, particularly if they happen to be porphyritic, for then the necessity arises of balancing the phenocrysts of one kind of feldspar against groundmass granules of another. Thus in some instances it may prove impracticable to specify the type of microgranite, but as with the coarse-grained equivalent types, distinction may sometimes be drawn between potassic microgranite and sodic microgranite. The former is a combination of either orthoclase or microcline with quartz and ordinary coloured minerals, usually biotite; while the latter is characterized by a sodium-rich feldspar (albite, microperthite or cryptoperthite) associated with such minerals as aegirine or riebeckite and, of course, quartz.

Texturally microgranites are variable—presumably as variable as the granites themselves. Porphyritic and aphyric types are widely distributed, though the former are probably the commoner. In porphyritic microgranites (formerly often called "quartz-porphyrries" or "granite-porphyrries") the phenocrysts may include alkali-feldspars, beta-quartz, and less commonly the dark silicates. The quartz phenocrysts have the form of more or less corroded bipyramids exactly as in rhyolites; while the orthoclase, when present, forms well-shaped crystals, though often to some degree sericitized or kaolinized. In microgranites associated with adamellites and granodiorites, plagioclase is an important constituent, and other things being equal, might be expected to occur as phenocrysts while the associated potassic feldspar would occur in the groundmass. The accessories occurring in these rocks are those normal in rocks of this composition; but in some, on account of their relatively late formation, normal accessories like zircon may be accompanied by others usually regarded as of pneumatolytic origin. The commonest of these is tourmaline, particularly in the minor intrusions associated with the granites of Cornwall and Devon.

A distinctive texture not uncommon among microgranites is the micrographic, which reproduces in miniature the graphic texture of granites of pegmatitic facies. In all such cases some part of the quartz and alkali-feldspar is intergrown, but there is considerable variation in the size, form and disposition of the components. Often the intergrowth forms a fringe around euhedral feldspar or quartz

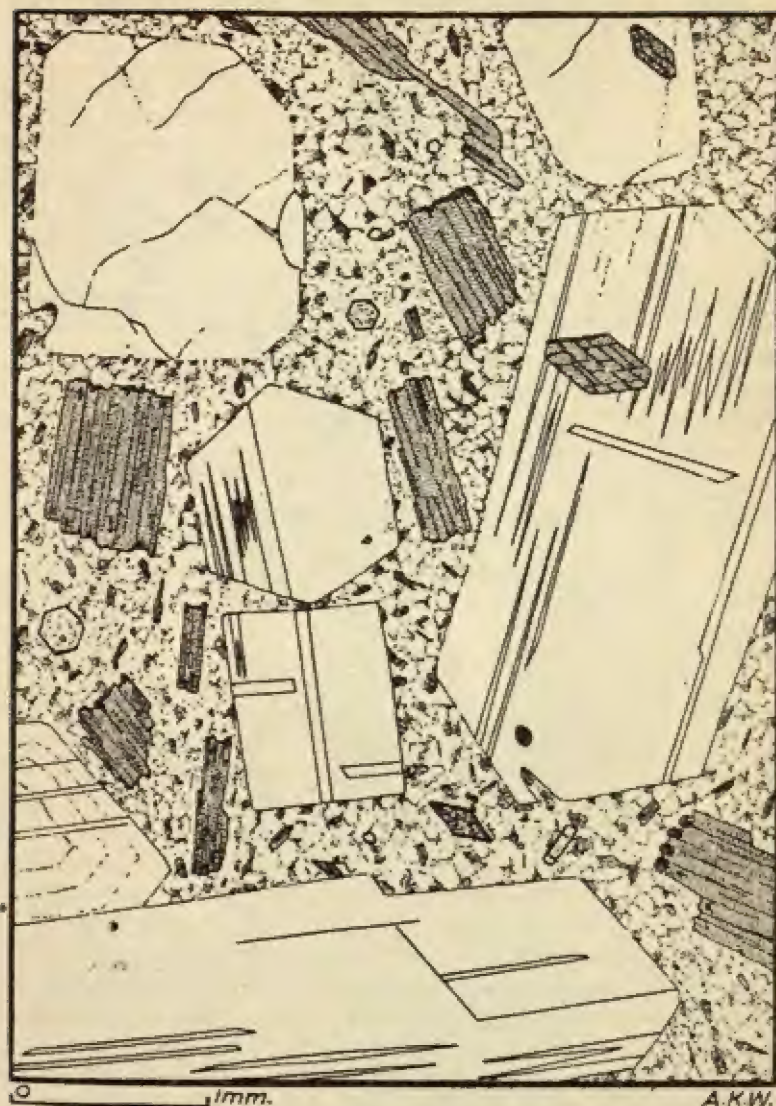


FIG. 88

Porphyritic micro-granodiorite, south of North Bend, British Columbia.

Phenocrysts of quartz, zoned plagioclase, common hornblende and biotite are embedded in a microcrystalline groundmass of the same minerals. Apatite and sphene are also shown. The twinning is indicated in the plagioclase.



FIG. 89

Granophyre, Fjardardal, Iceland.

Orthoclase is shown stippled, quartz black and white.

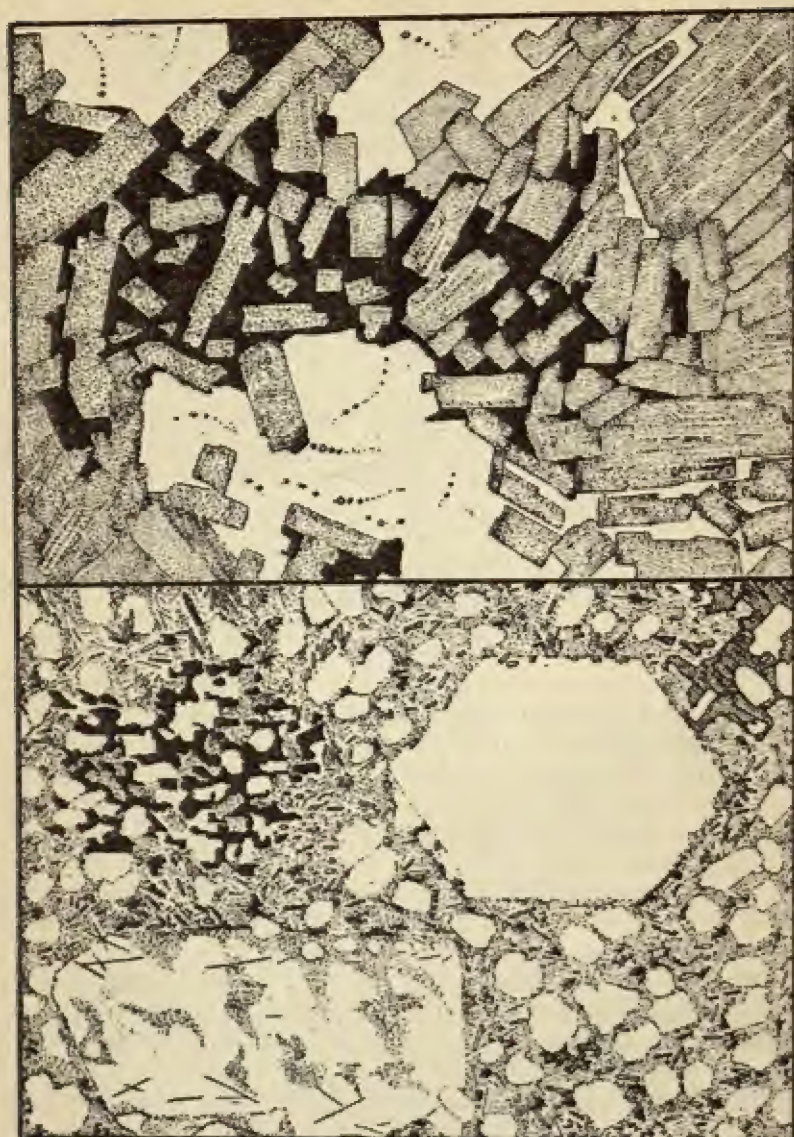
crystals, with an approximately radial disposition of the quartz elements. The intergrowth becomes progressively finer in a representative collection of such rocks, and the micrographic grades imperceptibly into the cryptographic, which demands the highest magnification before it can, with difficulty, be resolved. These latter are, of course, fine-grained, and arbitrary limits of grain-size are needed to separate graphic granites from graphic microgranites, and these in turn from cryptographic rhyolites. The same grain size limits may be used, but the limiting diameters refer to optically continuous patches of quartz or feldspar. "Graphic microgranite" is a self-explanatory term; but these rocks have long been known as **granophyres** (Fig. 89).

Until quite recently all granophyres were regarded as normal magmatic rocks; but some appear to have arisen by metasomatism of sedimentary rocks in some instances, and of pre-existing igneous rocks in others. Thus in the Karroo, S. Africa, shale has been metasomatised by dolerite sills to such a degree that it has been rendered mobile and has acquired intrusive relationships. This "mobilised" material has crystallized to form granophyre veins.¹ On the other hand it is claimed that on Slieve Gullion, Ireland, a Tertiary granophyre has been produced by metasomatism of a Caledonian granodiorite.²

Examples of microgranites are widely distributed. Types corresponding in composition with the alkali-granites are associated with, and occur as offshoots from, major intrusions of this nature. Thus the coarser-grained dyke-rocks, locally termed "elvans," found in the near neighbourhood of, or actually cutting the Cornish and Dartmoor granites, are potassic or sodi-potassic microgranites. Those with adamellititic and granodioritic affinities tend to occur in association with, for example, the Caledonian "granites" of these types in Scotland. Many of the minor intrusions in the English Lake District provide typical specimens of microgranites: the St. John's Vale intrusion, characterized by phenocrysts of orthoclase, quartz and small red garnets, is a porphyritic potassic microgranite. Among types which are correspondingly sodic we may note **riebeckite microgranite**, which occurs at Ailsa Craig in the Firth of Clyde, on Holy Island off the coast of Arran and at Mynydd Mawr in North Wales (Figs. 90 and 91). Although closely similar in mineral composition, the two examples figured differ in textural detail. The micropoikilitic habit of the riebeckite, sometimes giving it a "mossy" appearance, is characteristic. **Aegirine-microgranite**

¹ "Karoo Dolerites of the Union of S. Africa," *Bull. Geol. Soc. S. Africa*, ix (1949), p. 591, etc.

² Reynolds, D. L., *Rep. of Int. Geol. Cong.*, London (1948), Pt. III, "Metasomatic Processes in Metamorphism," pub. 1950, p. 20.



A. K. W.

FIG. 90 (above).—Riebeckite microgranite, Ailsa Craig, Firth of Clyde, Scotland. Alkali-feldspar embedded in poikilitic riebeckite (shown black) and quartz,

FIG. 91 (below).—Riebeckite-acmite-microgranite, Mynydd Mawr, Carnarvonshire.

Phenocrysts of β -quartz and alkali-feldspar in microcrystalline groundmass, with acicular prisms of acmite, and micropoikilitic riebeckite.

occurs among the dyke rocks connected with the alkali-syenite complexes of Sutherlandshire, for example the Cnoc na Sroine complex in Assynt.¹

It may be noted that the Ailsa Craig rock has been called "riebeckite-aplite." But the term "aplite" implies not only a peculiar mineral composition and a distinctive texture, but a special mode of origin. Unless there are strong grounds for believing that the rock in question has originated in the manner described above under "aprites" (p. 207), the term aplite should definitely not be used.

One of the best known British examples of graphic microgranites is that which occurs at Carrock Fell: the intergrowth in this case is relatively coarse. The rock forming the Armboth dyke in the Lake District is a handsome porphyritic variant with phenocrysts of quartz, bright red orthoclase and small garnets set in a dun-coloured graphic groundmass. The prominent Fort Regent mass lying on the outskirts of St. Helier, Jersey is only in part medium-grained, but is beautifully micrographic in places; while a massive columnar sill, in the main a rather fine-grained granophyre, forms the formidable scarp feature of Cader Idris in North Wales.

THE RHYOLITES

If for the sake of simplicity one name is required to include all the Acid igneous rocks of fine grain, it must be rhyolite, which thus has the same status as "granite" for coarse-, and "microgranite" for the medium-grained rocks. This is one of the older rock names, and was used by von Richthofen (1860) on account of the flow banding frequently exhibited by these rocks. They have also been termed liparites (Roth, 1860), from well-known occurrences in the Lipari Islands.

The upper limit of grain size is 0.05 mm., this having reference to the diameters of quartz or feldspar grains in the groundmass. Grains of this size are, of course, irresolvable with the naked eye, so for practical purposes the dividing line between microgranites and rhyolites can be placed at the limit of unaided vision for the groundmass components. No limit of size is laid down concerning the phenocrysts which are present in many specimens.

In attempting to subdivide this large class, we try to apply the same criteria as for the granitic rocks, and recognize three main categories based on the feldspar contents. It must be realized, however, that in many cases on account of fineness of grain or the presence of natural glass, it is impossible to apply any but a general name: specific identification along these lines is impossible. With an analysis available, the task is much simplified, of course.

¹ Shand, S. J., *Trans. Geol. Soc., Edinburgh*, ix (1910), pp. 397 and 399.

THE ALKALI RHYOLITES

In the scheme of classification these are exactly analogous to the alkali-granites and microgranites, and like them, may be further subdivided into (a) potassic and (b) sodic types.

Potassic Rhyolites.—In these the feldspar consists of the high-temperature form of orthoclase—sanidine, often in the form of glassy clear phenocrysts and/or as minute granules or microlites in



FIG. 92

Devitrified porphyritic pitchstone, Petit Portelet, Jersey, C.I. Highly corroded phenocrysts of quartz in "felsitic" (originally glassy) groundmass.

the groundmass. Sodic plagioclase is not excluded, but must be subordinate to the sanidine. In all rhyolites free silica may be present not only as β -quartz, but also as tridymite and even cristobalite. Of these the β -quartz is by far the commonest of the three, and the only obvious form of silica even under expert examination. It occurs as well-formed bipyramids, which, however, may show any degree of magmatic corrosion, and in extreme cases may be reduced to shapeless wrecks of the original crystals (Fig. 92). By comparison with granite one would expect the micas and hornblende to be the most commonly occurring coloured silicates; but actually although biotite is common, hornblende is rare in rhyolites, while pyroxene is widely distributed. This is consistent with the higher

temperature at which consolidation took place in the case of rhyolite, and the boiling off, instead of retention, of volatiles in lava flows doubtless also favoured the crystallization of the anhydrous pyroxene. The biotite is often very strongly coloured, so that basal sections appear almost black. The pyroxene is often nearly colourless—actually a very watery light green—in thin section, and is a diopsidic augite.

Sodic Rhyolites.—Like sodic granites these rocks may be very

ANALYSES OF ALKALI-RHYOLITES

	I. Potassic rhyolite.	II. Pitchstone, Arran.	III. Sodi-potassic rhyolite- obsidian.	IV. Sodic- rhyolite (Pantellerite).
SiO ₂	73·76	73·20	75·52	68·63
Al ₂ O ₃	11·98	10·75	14·11	0·35
Fe ₂ O ₃	1·14	0·95	1·74	10·30
FeO	2·40	1·02	0·08	5·60
MgO	0·76	0·15	0·10	2·61
CaO	0·32	0·76	0·78	0·37
Na ₂ O	0·53	3·78	3·92	1·07
K ₂ O	7·38	4·20	3·63	6·14
H ₂ O	1·75	4·70	0·39	4·17
TiO ₂	0·12	0·16	—	0·53
Other constituents	0·34	0·61	0·11	0·23
	100·48	100·28	100·38	100·00

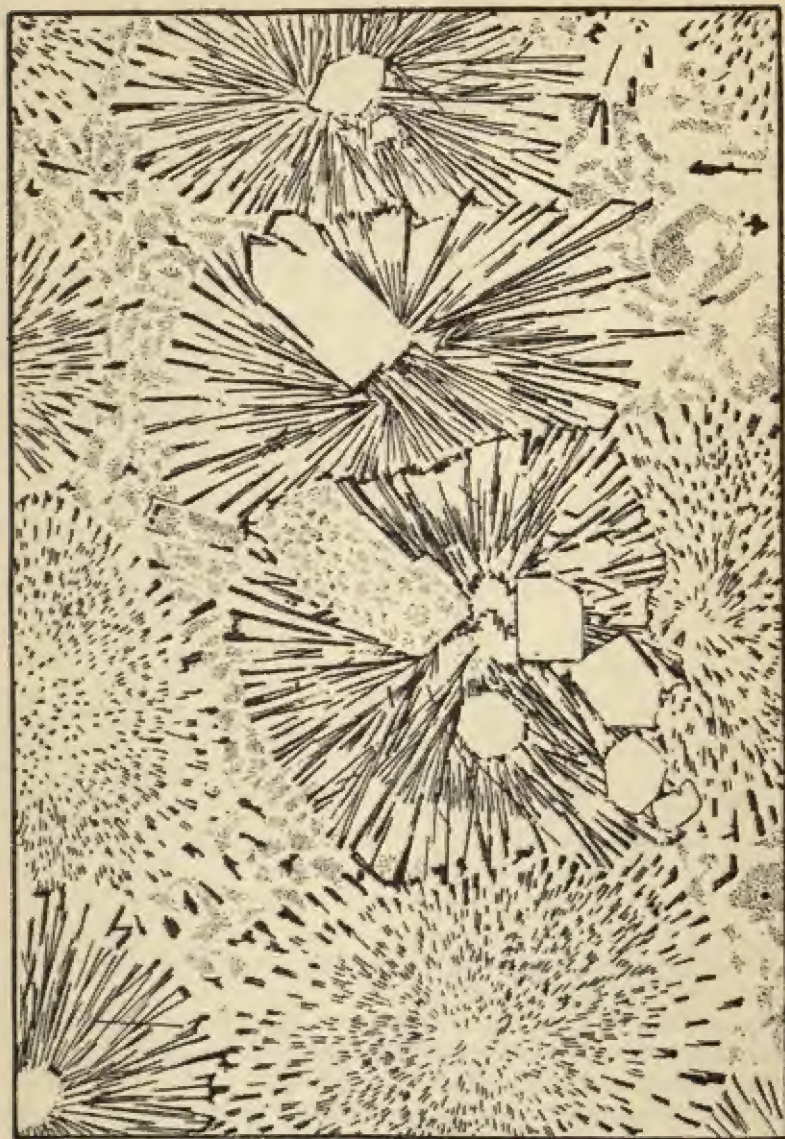
I. Potassic rhyolite, Cwm Caregog, Snowdon (Anal. R. J. C. Fabry), *Q.J.G.S.*, 1927, p. 368.

II. Sodi-potassic pitchstone, Arran, Scotland (Anal. E. G. Radley), *Geol. of Arran, Mem. Geol. Surv.*, 1928.

III. Obsidian, Obsidian Cliff, Yellowstone National Park, U.S.A. (Anal. Whitfield).

IV. Sodic-rhyolite (Pantelleria type). Average of twelve pantellerites quoted from Daly, 1933, p. 10.

distinctive, largely by reason of the coloured silicates they contain, which may be the same as those already described in the corresponding granites: viz., aegirine among the pyroxenes and riebeckite among the amphiboles being characteristic. The coloured silicates are accompanied by quartz, of course, and ideally by albite, though in very many instances the feldspar, as in the corresponding coarse-grained rocks, is sodi-potassic—a perthite or antiperthite of sorts. There is not the slightest doubt that these rocks, which occur as lava flows and minor intrusions, have had a common magmatic origin



M.K.W.

FIG. 93

Spherulitic riebeckite-rhyolite, between Rishi and Ayaka Leru,
northern Nigeria.

with the corresponding granites with which they are associated in the field, for example in the (sodic) alkali-complexes of Nigeria. Some types of sodic rhyolite have been given specific names. Thus "quartz-pantellerite," so named by Washington from occurrences on the island of Pantelleria, near Sicily, contains in order of abundance, "soda-microcline" (about $\text{Ab}_{30}\text{Or}_{70}$), quartz, aegirine, or aegirine-augite, and the distinctive and rare amphibole, cossyrite. "Quartz-keratophyre" has been used in several senses, but the practice in this country is to apply it to sodic rhyolites characterized by the presence of albite or albite-rich feldspar, associated with a little coloured silicate, the original nature of which has become obscure through alteration: they are represented by uninformative patches of chlorite. Lavas and texturally similar minor intrusives of this type occur among the Ordovician and Devonian eruptive rocks of North Wales and Devon and Cornwall respectively. The name obviously has no advantage over soda-rhyolite, and we do not advocate its use.

THE TOSCANITES

The **toscanites**¹ are the more acid members of the trachy-andesite series. They correspond to the adamellites among the plutonites. The toscanites may contain phenocrysts of both potassic-feldspar and plagioclase (oligoclase to andesine), together with quartz and a ferromagnesian mineral (biotite, augite or hypersthene) embedded in a groundmass that is frequently glassy. Biotite is the most prominent ferromagnesian constituent. Chemically the rocks are distinguished by high silica and alkalis and (for the acidity) high lime and low alumina. According to Washington, rocks of this type are found at Bracciano, Cervetere, Tolfa and Monte Amiata, in Central Italy.

THE DACITES

Dacites may be defined as occupying the position among the fine-grained igneous rocks, of the granodiorites among those of coarse-grain size. In terms of mineral contents, this implies a marked predominance of plagioclase over potassic feldspar, to the extent of at least two-thirds of the total feldspar. Theoretically dacites, like other types of acid lavas, may contain phenocrysts, or may be free from them. In practice the name is seldom applied unless phenocrysts of both quartz and plagioclase are present. Clearly only a portion of the total free silica will be visible as phenocrystic quartz—much of it will be retained in the groundmass, and a chemical check is desirable in doubtful cases. Further, while it was practicable

¹ From Toscana, the Italian for Tuscany. Name introduced by H. S. Washington, *Journ. of Geol.*, v (1897), p. 37.

to differentiate between granodiorites and quartz-diorites when dealing with rocks of coarse grain, this is impracticable in the fine-grained category. Thus quartz-andesite, strictly analogous to quartz-diorite, cannot be separated from dacite, and strictly speaking, the definition at the head of this paragraph should be modified accordingly, although it is of no practical importance.

Textural range of the rhyolites.—The rhyolites which capture the popular imagination are undoubtedly the vitreous types. Although the proportion of glass to crystalline mineral in rhyolites is infinitely variable, those types richest in glass are termed obsidian, pitchstone or pumice. At its best **obsidian** is a pure natural glass of rhyolitic (or granitic) composition, black in colour, naturally vitreous in appearance, and usually exhibiting a striking conchoidal fracture. Obsidian may be easily trimmed up to any desired shape—to a point or sharp cutting edge, for example; therefore this rock has been largely used by primitive peoples in the manufac-

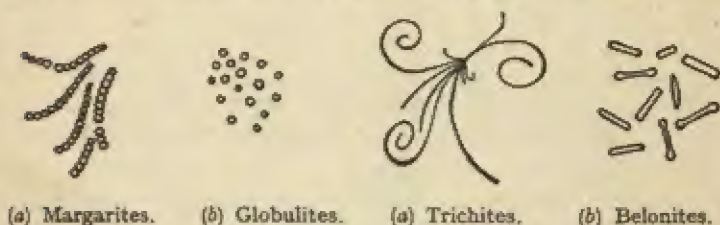


FIG. 94
Some types of crystallites.

ture of stone implements and weapons. Although obsidian is the commonest of the natural glasses, it is not widely distributed, the occurrences at Obsidian Cliff in the Yellowstone Park, at Mt. Hecla in Iceland, and in the Lipari Isles, being the best known. In thin section obsidian is colourless and isotropic. It is rarely completely devoid of crystalline material, which may occur as minute scattered crystallites (Fig. 94), or spherulites, either isolated, in irregular groups or trains, or in definite bands (spherulitic obsidian). Although the proportion of glass in **pitchstone** is very high, there is much more crystalline material than in obsidian. It may take the form of phenocrysts, of any of the minerals appropriate to rhyolites— β -quartz, sanidine, oligoclase, light green pyroxene are all common—or as microlites. The latter have been identified in some cases as feldspar, in others as pyroxene, presumably of the same type as that occurring as phenocrysts. The microlites may appear rod-like in thin section, but in some cases they form stellate or feathery groups, or may resemble fern fronds. In these

glassy rhyolites of both types flow structure is common: it is shown sometimes by the parallel alignment of the microlites which may sweep round phenocrysts like eddies in a stream, and convey a vivid impression of the viscous flow of the magma. In other cases the glass itself is colour-banded (Fig. 96), or layers of vitreous and non-vitreous lava may alternate, doubtless resulting from a degree of heterogeneity in the lava. Perlitic structure, resulting from tension set up by contraction during cooling, occurs in both obsidian and pitchstone (Fig. 97). These two terms are used rather loosely: in the opinion of some the distinction between them should rest on the

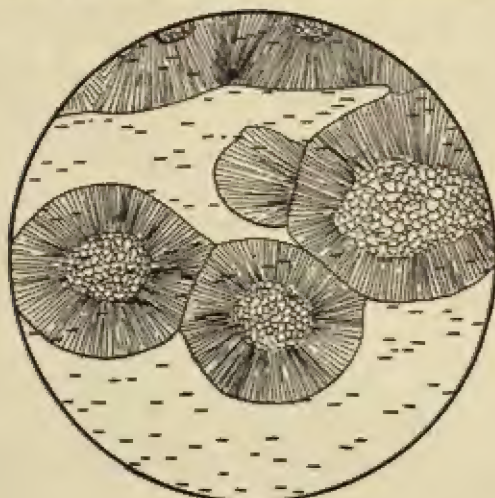


FIG. 95

Spherulitic Rhyolite-Obsidian, Lipari.

Showing belonites arranged by flow movements prior to the growth of spherulites.

different degree of crystallinity, as noted above; but in the opinion of others, the difference in water content is more significant. In obsidian the amount is small—usually less than 1 per cent—while in pitchstone it may rise as high as 10 per cent. Johanssen has advocated drawing the line at 4 per cent of water, but although this would make for accuracy, it is a drawback being unable to name a specimen until an analysis is available.

The common occurrence of glassy rocks among the rhyolites is regarded by Vogt as a natural consequence of the composition of the magma from which they were formed. The chief components, alkali feldspar and quartz, are present in nearly eutectic proportions. Such a mixture remains in the liquid state longer and at a lower



FIG. 96

Porphyritic pitchstone, Sgurr of Eigg, Hebrides.

The corroded phenocrysts are of β -quartz and sanidine: they have been chipped and the fragments scattered by the flow, indicated by the banding.

temperature than a magma of different composition. At temperatures near the eutectic, crystallization is inhibited by the high viscosity.¹

As regards mode of occurrence glassy rhyolites, equally with those

¹ Hawkes, L., "On Rock Glass and the Solid and Liquid States," *Geol. Mag.*, 1930, p. 17.



FIG. 97
Perlitic obsidian.



FIG. 98
Pitchstone, Corriegills, Arran, with pyroxene crystallites
surrounded by zones of clear glass.

of other types, may occur both as extrusive flows and intrusive sills and dykes. In Britain famous examples of pitchstones occur among the Tertiary intrusives in the Hebrides, in Arran and Eigg. The Arran pitchstones are well known on account of the interesting textures they exhibit (Fig. 98). Further, some contain iron-olivine, fayalite, in addition to more ordinary pyroxene, feldspars and quartz phenocrysts (Fig. 99). Most teaching collections contain specimens of the Meissen pitchstones which are reddish in colour, and are mostly lavas. Pitchstone lavas occur also among the Old Red Sandstone volcanics in the Cheviot Hills.

All these glassy rocks tend to change their character spontaneously in the course of time, when they become devitrified. Although evidence of their originally glassy nature may be clearly proved by traces of perlitic structure, for example, examination between crossed polarizers shows them to be completely crystalline—often quite coarsely microcrystalline, the whole rock breaking up into a mosaic of ill-defined grey-polarizing areas bearing no relation whatever to the original structure. This is often called felsitic texture, and the rock itself a felsite, which is therefore merely an ancient devitrified rhyolite. Many examples of these occur among the lavas of Uriconian age in Shropshire, and of Ordovician age in North and South Wales.

It was mentioned incidentally above that these rocks may be spherulitic. Ideally the spherulites consist of near-spheres, often about the size of a pea, but varying from smaller than a pin's head to larger than a man's fist. In the case of the smaller ones a section shows the spherulites to consist of radially disposed fibrous crystals, which are not easily identified under the microscope. In some cases they contain cristobalite, or may consist of it.¹ In certain rhyolites the whole of the groundmass may be spherulitic: the characteristic radial arrangement of fine microlites may be seen, particularly between crossed polarizers, although on account of mutual interference during growth the individual spherulites are no longer spheres but they may be recognized by the imperfect black cross that results from the straight extinction of the individual fibres. The French name "pyromerides" is still applied to the spherulitic rhyolites of the north coast of Jersey, Channel Isles, which are perhaps unique. The spherulites often show a strongly developed concentric structure, superimposed upon the more normal radial arrangement. In this respect they are allied to the so-called lithophysae—stone bubbles which superficially resemble spherulites but are hollow inside.

With slower cooling the rhyolitic magma will not congeal as glass, but will become wholly crystalline. There may be difficulty in deciding whether this holocrystalline condition is original or the

¹ Howard, A. D., *Amer. Min.*, xxiv (1939), p. 485.

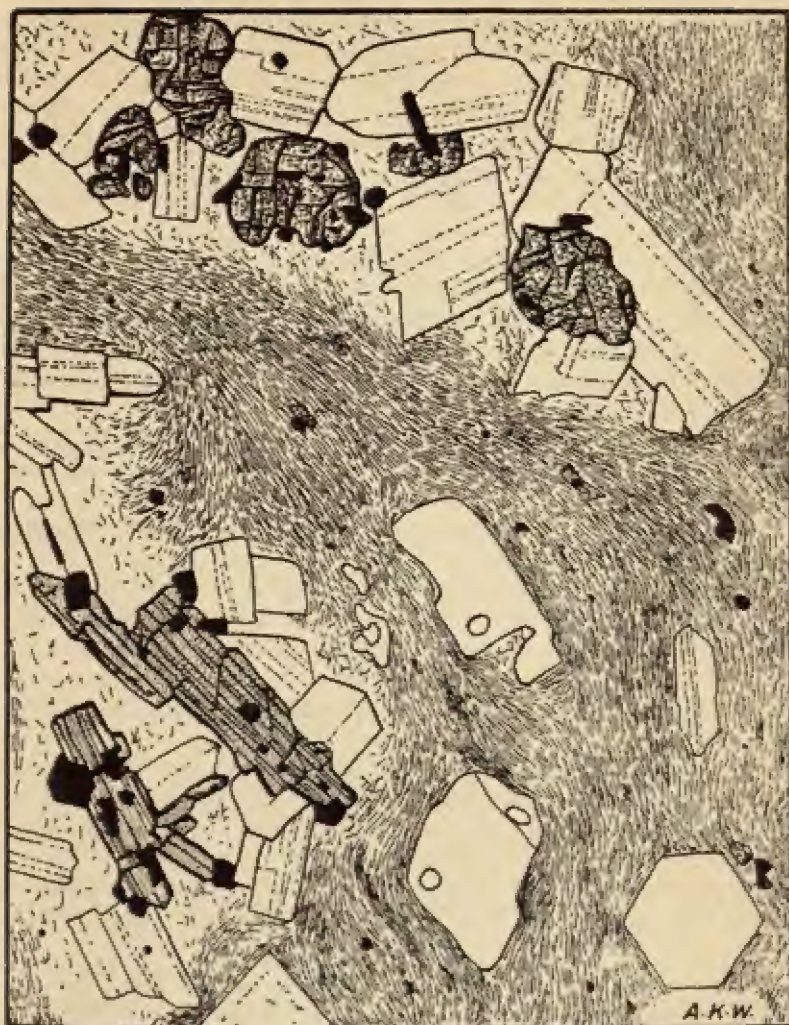


FIG. 99

Fayalite-pitchstone, Glen Shurig, Arran. Fayalite phenocrysts occur in the upper half of the section, a greenish clinopyroxene in the lower half. Iron ore, plagioclase and β -quartz are also present, the latter giving typical hexagonal basal section.

result of devitrification; but in the absence of relics of the glassy state, referred to above, and if the individual grains are clearly defined, it is almost certainly an original structure. As noted above, rhyolites may be porphyritic to any degree: the phenocrysts may

be minute and widely scattered, or they may be relatively large and so closely packed as almost to exclude the groundmass. The name "nevadite" was applied by von Richthofen to a rock of the latter type. It is best, however, to introduce new names for rocks with distinctive mineral composition, rather than some mere textural peculiarity, which can always be covered by appropriate qualifiers. Richness in phenocrysts is not an attribute of one kind of rhyolite, however, and while one lava described as nevadite is a phenocryst-rich potassic rhyolite (with porphyritic sanidine and quartz), another has been called by the same name on account of the abundance of phenocrysts, but as they include oligoclase, biotite and hornblende in addition to sanidine and quartz, we are dealing with a rock in a different category altogether: it is a phenocryst-rich dacite (p. 223).

CHAPTER III

THE INTERMEDIATE IGNEOUS ROCKS

IN this category we include the Syenite, Syenodiorite (or Monzonite) and Diorite Clans. Ideally these rocks should contain no quartz, this being the mineralogical basis of the distinction from those designated "Acid." The coloured silicates play a minor rôle, whereas the conditions are reversed in the Basic rocks. It follows, therefore, that the feldspars are typically the most important components, and again there is full justification for using these minerals as the basis of further subdivision. As with the Acid rocks, three degrees of alkalinity are recognized, and are expressed in terms of the ratio of alkali-feldspar to plagioclase. There is general agreement on the need to distinguish syenitic rocks, in which alkali-feldspar predominates, from dioritic rocks in which plagioclase is dominant. Opinion is divided as to whether it is necessary to find a place in the scheme of classification for a group in which the two kinds of feldspar are of approximately equal importance. As stated above, we believe that the gain in precision resulting from the recognition of three, rather than two groups, more than offsets the extra trouble involved in measuring the proportions of the feldspars. The outline scheme of classification of the Intermediate rocks is shown in the appended table:—

Grain Size.	Alkali-Feldspar > $\frac{1}{2}$	Alkali-Feldspar and Plagioclase each between $\frac{1}{2}$ and $\frac{1}{3}$	Plagioclase > $\frac{1}{2}$
Coarse	SYENITES	SYENO- DIORITES (MONZONITES)	DIORITES
Medium	MICRO- SYENITES	MICRO- MONZONITES	MICRO- DIORITES
Fine	TRACHYTES	TRACHY- ANDESITES	ANDESITES

(a) THE SYENITE CLAN

The members of the Syenite Clan are rocks of intermediate composition, characterized by the mineral combination, alkali-feldspars and coloured silicates, the former in typical specimens being largely dominant. They may contain plagioclase within the range oligoclase-andesine up to one-third of the total feldspar content. Within the Clan three grain-size groups are erected, coarse, medium and fine, comprising the syenites, microsyenites and trachytes respectively. Each of these groups may be further subdivided, according to the dominant alkali, into a potassic series and a sodic series. At this point a new principle is introduced into the scheme, for in the Intermediate category unsaturated minerals—the feldspathoids—may take the place of the (saturated) feldspars in varying degree. Further, although ideally syenitic rocks should contain no quartz, in fact they grade into those of granitic composition, and it is eminently reasonable to include among the syenites those rocks which, although essentially syenitic, yet contain the characteristic mineral of granites—quartz—in a subordinate rôle. We agree with Shand in allowing a latitude of 10 per cent, but distinguish these over-saturated syenitic rocks as quartz-syenites, quartz-microsyenites or quartz-trachytes according to their grain-size.

THE SYENITES

When on general grounds a rock has been classified as a syenite it is usually relatively easy to decide whether or not it is an under-saturated type, though in many cases a thin section is necessary. If no feldspathoid is discovered, the rock will be over-saturated if it contains any quartz, or saturated if that mineral is absent. Thus all syenites belong to one of three categories: (a) quartz-syenites, (b) orthosyenites, (c) feldspathoid-syenites. The condition of exact saturation is rarely achieved, and therefore orthosyenites (the ideal types) are correspondingly rare: most specimens prove to be slightly over-, or slightly under-saturated. For purposes of description quartz-bearing and quartz-free types are considered together; the feldspathoidal types are described separately.

(a) QUARTZ-SYENITES AND ORTHOSYENITES

In some of these rocks the feldspar is indubitably potassic; in others it is equally clearly sodic. This suggests the possibility of distinguishing potassic syenites from sodic syenites, and in many cases this can be done, but there are difficulties. It may prove impossible merely by inspection to estimate the balance of the alkalis, for the potash and soda are often inextricably mixed in the perthitic feldspars. Further, a portion of the soda is frequently locked up in the

coloured silicates such as aegirine. In any case, however, reference of a particular rock to one or other of these series is a matter of academic interest only: all the types of syenites are named on the basis of their mineral contents, not on their alkalinity. Notwithstanding this, however, it is a matter of convenience to deal first with the typical potassic syenites, then with the sodic types.

The rock of Syene (Assouan) in Egypt, from which Pliny derived the word syenite, contains much quartz, and is, in fact, a particularly handsome hornblende-granite. The rock selected by A. G. Werner as representative of the type comes from Plauen, near Dresden, and is commonly known as the **Dresden syenite**. Werner's purpose was to establish a type of feldspathic igneous rock having a granitic texture, but distinguished from granite by the absence of notable amounts of quartz. But in spite of its popularity, the Dresden syenite is not typical of its class in two respects: it contains too much quartz (from 6 to 12 per cent), and too much oligoclase in some samples, the range being 3 to 37 per cent. Obviously not all of the intrusion is syenite: the specimens with more than 10 per cent quartz are granites; while those with the largest amount of oligoclase are definitely monzonitic. Such variation is to be expected, as the Dresden syenite is a satellite of the Meissen granite.

In thin section the orthoclase, uniformly twinned on the Carlsbad law, shows undulose extinction due to strain, and must be carefully distinguished from the oligoclase which has the same habit, and displays Carlsbad twinning much more obviously than the Albite twinning.

Tyrrell¹ has described from Spitzbergen a syenite much nearer to the ideal type. It is only just over-saturated (quartz, 3.3 per cent); feldspar makes up 70 per cent of the rock, and is almost entirely microcline (66 per cent, with only 4 per cent oligoclase). Coloured silicates make up a quarter of the rock, biotite and augite being approximately equal.

Ideally in sodic syenites the feldspar should be either albite or an albitic antiperthite. **Albitite** is of very rare occurrence; but since its discovery in Plumas County, California (H. W. Turner, 1896), it has been found at Cape Willoughby, South Australia, and latterly in the Shetland Isles, Scotland.² Albitite is nearly monomineralic, as albite is the sole essential component: accessories occur in minute amounts, and although its silica percentage is so high (68) quartz does not typically occur. Naturally albitite is white in hand specimen, and is an extreme example of sodic leucosyenite.³

¹ *Trans. Roy. Soc., Edinburgh*, liii (1922), p. 225.

² Walker, F., "An Albitite from Ve Skerries, Shetland Isles," *Min. Mag.*, xxiii (1932), p. 239.

Syenites are rarely so extreme in composition as the Spitzbergen syenite on the one hand, and albitite on the other: as noted above, the majority are sodi-potassic. **Perthosite**¹ (which would have been equally well-named had "perthitite" been chosen instead) is a good example of a sodi-potassic leucosyenite. With less than 5 per cent of dark minerals, the type-rock consists of little else than micropertthitic feldspars. Analysis shows the rock to contain 65 per cent of silica, and, as might be anticipated, very high alkalies, with soda (7.4 per cent) slightly in excess of potash (5.2 per cent).

One of the first of these sodi-potassic syenites to be specifically named, and which has since proved to be fairly common, is **nordmarkite**, described by W. C. Brögger² from Nordmarka, immediately north of Oslo. The type may be concisely described as a sodi-potassic quartz-syenite which approaches some granites in composition. The chief component is a reddish orthoclase intergrown with albite. Although the amount of coloured silicates is small, near to the 5 per cent mark, riebeckite, aegirine and arfvedsonite may all occur. In Britain a syenite very near to nordmarkite forms the highest parts of the stratified laccolith of Cnoc na Sroine in Assynt, northern Scotland, and occurs also in the alkali-complexes of Ben Loyal³ and Loch Ailsh in Sutherlandshire.

A very distinctive type, both as regards megascopic and microscopic characters is the very handsome Norwegian rock, widely used for ornamental purposes, and termed **larvikite** (or **laurvigite**) by Brögger (1890). The type is characterized by its coarse grain and distinctive feldspars, which, especially on polished surfaces, exhibit a beautiful blue schillerization. They were referred to as anorthoclase and were regarded as a cryptoperthitic intergrowth of orthoclase and oligoclase. In this respect they are akin to the feldspars in the lava-type, kenyte (p. 252). Recently, however, it has been claimed that instead of a single feldspar-phase, there are *two* present—oligoclase and alkali-feldspar. The former is largely antiperthitic and it is exceedingly difficult to identify as it rarely shows twinning. Actually the plagioclase member is intricately twinned on the Albite Law, but on so fine a scale that the lamellae are invisible under ordinary conditions. To complicate the issue still further, the twinning imparts a monoclinic symmetry to the optical orientation of the crystals. This elusive internal structure finds outward expression in the develop-

¹ We use the prefix "leuco" to indicate light colour due to the very small amount of coloured silicates present. The upper limit of the latter is taken at 5 per cent.

² Phemister, J., "Geology of Strath Oykell, etc.," *Mem. Geol. Surv. Scotland* (1926), p. 47.

³ Read, H. H., in "Geology of Central Sutherlandshire," *Mem. Geol. Surv. Scotland*, 1931, p. 174.

⁴ *Syenitpegmatitgänge*, 1890, p. 34.

ment of a distinctive crystal habit under favourable conditions, well exemplified in the rhomb-porphyrries described below. Larvikite has always been regarded as a syenite, but in view of these facts, its retention in this family is questionable: some larvikites appear to be monzonitic in composition: the *substance* of oligoclase is present in the requisite proportion, whether it is intimately intergrown with the alkali-feldspar, or occurs in discrete crystals.¹ The specimen illustrated in Fig. 100 is apparently syenitic, however, and so far as superficial characters are concerned, it would be out of place among the monzonites. Larvikite grades into lardalite, in effect a nepheline-larvikite, but with albite in place of oligoclase.

On account of the dark colour of the feldspars, the coloured silicates are not obvious in larvikite, but are very distinctive in thin section (Fig. 100). These minerals occur in clots, and would be more "at home" in a Basic than in an Intermediate rock, for they comprise olivine (a fayalitic variety), and purplish augite, strongly schillerized and irregularly rimmed with barkevikite. Lepidomelane moulds itself upon irregular masses of iron ore, while apatite in unusually large crystals is a constant accessory.

Another type of sodi-potassic syenite is **pulaskite**, named from the type locality, Pulaski County, Arkansas (J. F. Williams, 1890).² Much of the twelve square miles occupied by the Ben Loyal Complex near Tongue in northern Scotland is occupied by syenite comparable with the original pulaskites. The chief component is antiperthite associated with a little aegirine and accessories. In the Arkansas rocks nepheline occurs in small quantity in some specimens, but is not invariably present. But in view of the significance of nepheline, one name must not be used for under-saturated as well as saturated types; and while "pulaskite" is appropriate to the latter, the former must be distinguished as "nepheline-pulaskite."

(b) UNDERSATURATED SYENITES: NEPHELINE-SYENITES AND RELATED TYPES

The rocks in this group have been classified in a variety of ways, and many of the rock-names in current use have different shades of meaning according to which authority is followed. Those critics who lament the multiplicity of rock-names find considerable cause for complaint in the nomenclature of the nepheline-syenites. Considering their comparative rarity, the number of named types is unduly

¹ Barth, T. F. W., "The Igneous Rock Complex of the Oslo Region"; ii, *Systematic Petrography of the Plutonic Rocks, Oslo*, 1945, p. 76; but cf. Öfstedahl, C., *ibid.*, Pt. ix. *The Feldspars* (1948), 71 pp.

² "The Igneous Rocks of Arkansas," *Ann. Rep. Geol. Surv. of Arkansas*, 1890, p. 74.

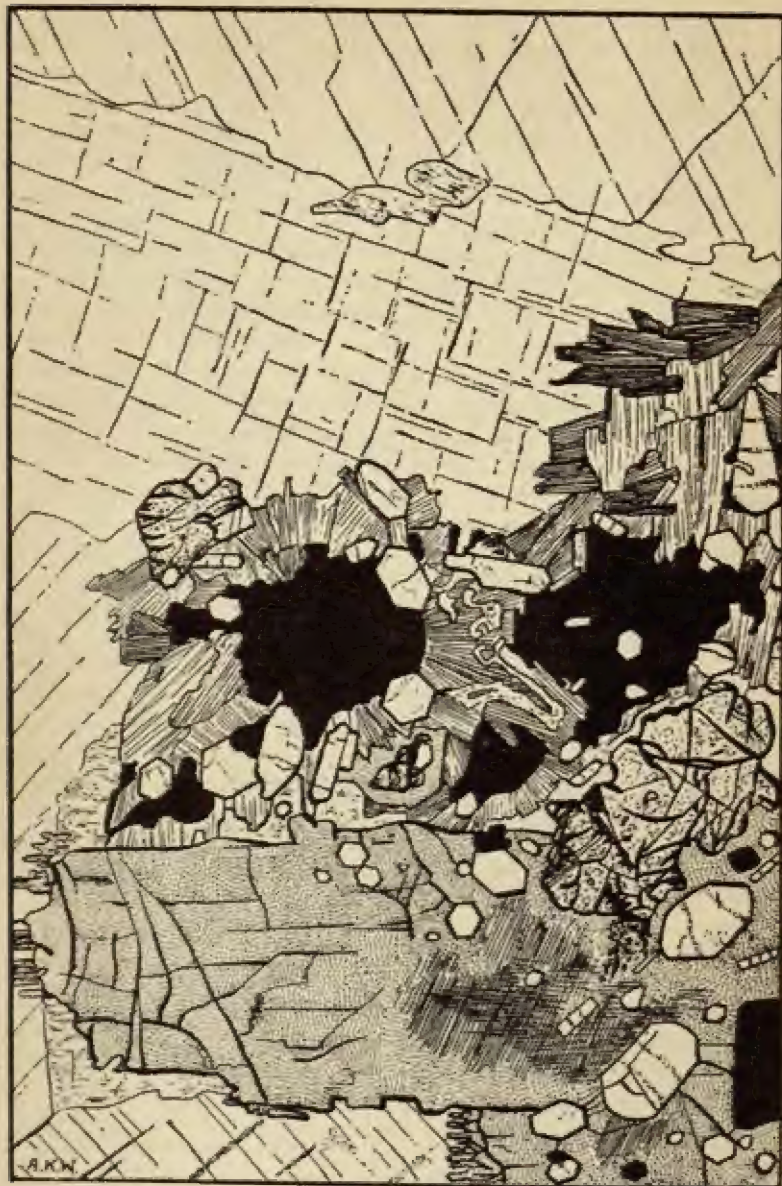


FIG. 100

Larvikite, Larvik, Norway.

Schillerized titanite, stippled; lepidomelane, lined; olivine, strong surface relief; titano-magnetite, black; apatite, plain. A little nepheline and much anorthoclase showing its cleavage.

large. Further, most of them were named at a time when only one principle was recognized—that of adding the uniform termination “-ite” to the place-name of the original discovery. As a consequence many obscure little places in Russia, Greenland, Norway, etc., have become immortalized as rock-names. Most of these names look strange to English eyes, and it is relief to meet “monmouthite” and “litchfieldite,” even when it is discovered that the type-localities are in North America. Naturally there is full justification for establishing sufficient types to cover the main mineral combinations. In order of importance due consideration must be paid to the nature of the feldspar with which the nepheline is associated; the ratio of feldspar to feldspathoid; the nature of the coloured components; and possibly even textural qualities. It must further be borne in mind that the place of nepheline may be taken by chemically related silicates, including sodalite, analcite and cancrinite; while in some types rare minerals which normally occur as accessories only, increase in amount until they have the status of essential components: eudialyte is a case in point.

On general grounds the association of albite with nepheline may be regarded as most typical of the under-saturated sodic syenites. The degree of under-saturation is widely variable, and therefore the ratio of albite to nepheline is correspondingly wide. As nepheline is a basic mineral, with very low silica percentage compared with albite, richness in nepheline goes with poorness in silica, and some types with a typically syenitic appearance—light colour and small content of dark silicates—are thoroughly basic. From most points of view it is a mistake to separate these rocks from the nepheline-syenites, with which they are genetically related. By contrast, the colour index of these rocks steadily increases until some have the aspect of basic, gabbroid rocks. Again their affinities are strongly with the nepheline-syenites; but on account of their melanocratic character, it appears to be inappropriate to group them with the syenites. We therefore group with the Basic rocks those consisting of nepheline, feldspar and coloured silicates, provided that the colour index is 40 or higher.¹ Of those containing less than 40 per cent coloured minerals, it seems desirable to recognize three types: (a) with albite in excess of nepheline; (b) with nepheline exceeding albite; and (c) with nepheline only.

(a) **Mariupolite** (Morozewicz, 1902) is a good example of the type in which albite heavily outweighs nepheline, the former making up approximately three-quarters of the rock, the latter only 13 per

¹ Having adopted the colour index of 40 to separate (Intermediate) diorites from (Basic) gabbros (p. 258), we use the same figure for a similar purpose here. The alternative would be to call these rocks “nepheline-melasyenites.”

cent, while in the type-rock aegirine (7.5) accompanies lepidomelane (4).

(b) **Monmouthite** is representative of the second category: it is complementary to mariupolite, as rather more than three-quarters of the rock consists of nepheline. The amount of coloured mineral is less than in mariupolite, but in spite of the low colour index, this rock contains only 40 per cent of silica.

(c) The extreme of this line of variation is represented by **urtite** which contains no feldspar. This thoroughly basic rock is described in a later chapter.

It may be noted that in each case the type-rock contains a specified coloured mineral (or minerals). Further discoveries may prove rocks to exist in which the ratio of feldspar to feldspathoid is the same, but the coloured minerals may be different from those in the type-rock. Such cases should be covered by the use of appropriate qualifying adjectives, rather than by the introduction of new names.

The types so far noted are rare, even among nepheline-syenites. In the great majority of cases, the feldspar is not pure albite, but either the latter associated with orthoclase, or an intergrown sodi-potassic type. **Litchfieldite**, named from Litchfield, Maine, is close to mariupolite in general character, but although albite is the dominant feldspar it is accompanied by microcline. The type-rock is white with scattered black lepidomelane crystals, lemon-yellow patches of cancrinite, and a little sodalite. For the sake of consistency we would prefer to name the type-rock sodalite-litchfieldite retaining the name without qualification for the combination nepheline, albite and orthoclase (or microcline), with coloured silicates in variety. Whether in such cases "cancrinite-" should be added to the rock-name must depend upon whether it is a primary constituent or not. If not, it is of no more significance than any other alteration product.

Foyaite, so named by Blum (1861) from the Foya Peak in the Serra de Monchique, Portugal, is probably the most widely distributed type of nepheline-syenite. It is a leucocratic coarse-grained rock consisting of nepheline, perthitic feldspars and subordinate coloured minerals. Specimens from several different alkali-complexes in various parts of the world appear to conform to a type in which roughly one-quarter of the rock is nepheline; potassi-sodic feldspar ("soda-orthoclase") makes up about 62 per cent, a sodic pyroxene some 10 per cent, and sphene and other accessories 5 to 6 per cent. The nepheline is usually interstitial to the flattened white tablets of feldspar, but may be euhedral. When somewhat weathered the nepheline turns red and contrasts strongly with the white feldspars

and black pyroxenes. In the Pilaansberg ring-complex a white sodalite-foyaite occurs, which "glitters in the sunlight like marble." Another occurrence described by Shand as foyaite should, in our opinion, bear a different name, for the feldspar is an apple-green microcline: *i.e.*, it is wholly potassic, and therefore the rock has the same status as mariupolite.

The mineral which most commonly acts as proxy for nepheline is the allied silicate, sodalite. As noted above, sodalite is liable to occur, in a very subordinate capacity, in such types as foyaite. As soon as it attains to the status of an essential component, a new name is required. **Ditróite**, described by Zirkel (1866) from Ditró in Transylvania, is such a rock. In it nepheline may be as abundant as feldspar (microcline-micropertthite in the type-rock), and is accompanied by both sodalite and cancrinite. The latter is apparently secondary after nepheline. While a green biotite occurs in some specimens from the type-area, aegirine-augite rimmed with very dark green arfvedsonite is more characteristic. Ditróite is a sodalite-bearing nepheline-syenite. Obviously with the rôles of the two feldspathoids reversed, the rock must be a nepheline-bearing sodalite-syenite. The true **sodalite-syenite**, containing no nepheline, lies at the end of this line of variation, and is represented by a rock to which this name was originally given, occurring at Julianehaab in Greenland. Sodalite is not particularly abundant in it, amounting to some 8 per cent, but is the only feldspathoid present. Much of it is interstitial to lath-shaped sections of microcline-micropertthite, but some of it occurs in the form of euhedral rhombicuboctahedrons embedded in the feldspar. It is thus obviously primary. Sodalite-rich syenites are rare; but an example from St. Hilaire Mt., Quebec, contains up to 70 per cent; while a facies of the sodalite-syenite in Greenland grades into an almost pure sodalite rock, of an intense blue colour.¹

* It is appropriate to consider **analcite-syenite** next, if for no other reason than the close similarity between sodalite and analcite. Both are cubic, colourless and have low refractive indices, and there is no easy optical method of differentiating between them: a micro-chemical test is the only certain means of distinction. "Analcite-syenite" used without qualifiers implies the association of analcite with alkali-feldspars and coloured minerals. G. W. Tyrrell² has described a coarse-grained analcite-syenite from an Ayrshire locality. The dominant mineral is anorthoclase rimmed with orthoclase, and it is accompanied by some plagioclase. The dark minerals are titanite rimmed with aegirine, and barkevikite. All these minerals

¹ Rosenbusch, *Mikroskopische Physiographie*, 1907, p. 240.

² *Quar. Journ. Geol. Soc.*, lxxxiv (1928), p. 540.

are embedded in an abundant matrix of analcite. In this locality the analcite-syenite forms the upper part of a composite sill, the lower part of which is a basic analcite-gabbro (crinanite). This suggests that analcite-syenite is a differentiate of a basic magma carrying the constituents of analcite. The occurrence of thin veins of the former in a differentiated teschenite sill at Hallcraig in Fifeshire¹ supports this hypothesis, as teschenite is closely similar to crinanite.

Any nepheline-syenite is liable to contain cancrinite. In many instances its relations to the nepheline indicate that it is an alteration product of the latter; but in other cases it is not only more abundant, but it has the status of an essential component, and in appearance seems to be primary. By analogy with other types considered above, such rocks are cancrinite-bearing nepheline-syenites (not cancrinite-syenites).

Nepheline-syenites and more particularly the pegmatitic facies are noteworthy on account of the wide variety of accessories they contain. Many of these are titanium and zirconium silicates. One of the more striking is eudialyte, which in some rocks is obvious in the hand specimen, and which rarely ranks as an essential component. **Eudialyte-nepheline-syenite**, named "chibinite" from a locality in the Kola Peninsula in the U.S.S.R. is a very striking-looking rock in the hand specimen: it consists of black aegirine prisms and bright cherry-red eudialyte² in a matrix of nepheline and microperthite.

Finally, reference may be made to another rare type—**corundum-syenite**—which occurs in the Haliburton-Bancroft area in Ontario³ and in the Ural Mountains.⁴ The rock from the latter locality contains no nepheline, but it falls in the category of under-saturated syenites in virtue of the presence of corundum. This mineral makes up nearly a quarter of the rock, most of the rest being microperthite, the third component being biotite in very small amount. The Canadian specimens on the other hand are corundum-bearing nepheline-syenites, often of pegmatitic facies. The origin of the corundum-bearing syenites is discussed in a later chapter.

RELATIONSHIPS AND ORIGINS

Syenites do not form large individualized intrusions, but occur as marginal facies of, or offshoots from granitic masses. The well-

¹ Campbell, R., "The Braefoot Outer Sill, Fife," *Trans. Geol. Soc. Edin.* xiii (1933), p. 148.

² This is a very different colour from the red altered nepheline seen in many foyaites; it is a "raw" deep pink. Further the eudialyte has a vitreous lustre: the altered nepheline is dull.

³ Adams, F. D. and Barlow, A. E., "Geology of the Haliburton-Bancroft area, Ontario," *Geol. Surv. Mem. Canada*, No. 6, 1910.

⁴ Morozewicz, J., "Ueber Korundgesteine des Ural . . .," *Tsch. Mitt. Petr. Min.*, xviii (1898), p. 217.

known Dresden syenite, for example, is a facies of the much larger Meissen granite. In such cases it is evident that the parent magma was acidic rather than syenitic, and that a portion of it suffered desilication to produce the syenite. This process probably involved reaction between the granitic magma and its roof- and wall-rocks. Syenites showing rather different relationships occur in the Bancroft area of the Canadian Shield. They surround elongated cores of hornblendite, and are themselves surrounded by granite, the implication being that the syenitic facies is a product of local reaction between granitic magma and ultramafic rock. Some of these Bancroft syenites are typical perthosites containing up to 99.5 per cent perthitic feldspar; but others contain quartz which increases as the perthites decrease, until it reaches over 26 per cent. These quartz-rich rocks are, of course, granites as defined above.

Trachytes, as explained below (p. 250), are associated in the field with basalts, and are commonly regarded as differentiates from a basaltic magma. The magmatic origin of these trachytes, therefore, is beyond question and there must locally at least be trachytic, that is syenitic, magma in the earth's crust. Naturally if this magma consolidates at a sufficient depth below the surface, syenitic rocks, produced by direct crystallization from a syenitic magma, must result. Thus syenitic rocks originate in two quite different ways. There is a third possibility. In theory basic magma may be enriched in silica and alkalis to the point of becoming "Intermediate" in composition, and potentially syenitic. A small scale demonstration of this process has been described from the island of Colonsay off the Scottish coast. Here hornblendite occurs which is heavily charged with xenoliths of quartzite, each one of which is insulated, as it were, by a narrow zone of syenite.¹ The extent to which direct feldspathization of country rock may give rise to syenite by ionic migration is still uncertain; but the possibility must not be overlooked.

Origin of the Nepheline-Bearing Rocks.

Nepheline-bearing intrusive complexes are rare, and the largest known are very small compared with the great acid and basic intrusives. The three largest are in the Kola Peninsula, U.S.S.R., Pilaansberg, a ring-complex within the Bushveld Complex in the Transvaal, and a part of southern Greenland: the areas of the nepheline-bearing rocks are 760, 200 and about 100 square miles respectively. In addition there are many smaller intrusions, some of which are well known by reason of the problems of origin and association they present.

As regards origin, there appear to be two important factors:

¹ Reynolds, D. L., *Min. Mag.*, xxiv (1936), p. 367.

firstly, concentration of volatiles, as evidenced by the coarse grain of the rocks, and by the extraordinary variety of rare accessory minerals found in them, particularly in those of pegmatitic facies. Secondly, the close, often intimate association with carbonate-rocks is significant.

Shand has made a careful study of these rocks, and has collected an impressive amount of evidence to support Daly's contention that the essential process concerned is **desilication** of the original magma as a consequence of assimilation of limestone.¹ Through the early separation of lime-bearing silicates, the magma is depleted not only of silica, but also of calcium and magnesium, with two important consequences. Firstly, the diopside molecule is not available for the pyroxenes and amphiboles, so that the place of common augite and hornblende in normal rocks is taken by the sodium-iron amphiboles and pyroxenes, which are almost invariably associated with the nepheline. Secondly, nepheline crystallizes in place of plagioclase. Among the lime-rich minerals produced during desilication, diopside, melanite garnet, sphene, apatite, melilite and perovskite are important, and tend to be concentrated in the more basic members of the complexes.

Apparently both granitic and basaltic magmas may suffer desilication in this way. In the Bancroft area of Ontario, within the outcrop of the Grenville Limestone, over twenty granitic intrusions are associated with foyaite, the latter being invariably marginal to the granite.² These constant field-relations strongly suggest, if they do not prove, desilication of the granite to produce the foyaite.

On the other hand, Tilley has described very fully a basaltic plug intrusive into Chalk, and in the contact-zone nepheline-bearing rocks have been developed on a small scale. Thus it appears that desilication of granitic or basaltic magma is one way in which nepheline-bearing rocks are produced.

Bowen has stated the case for the genesis of feldspathoidal rocks in ways which do not involve limestone assimilation. He claims that a magmatic fraction of the requisite composition to yield feldspathoids, may result during the normal course of crystallization differentiation. The original magma is believed to contain potential KAlSi_3O_8 as well as $\text{NaAlSi}_3\text{O}_8$. With a particular concentration of volatiles, particularly (OH), the feldspar molecules tend to break down into KAlSiO_4 and NaAlSiO_4 and silica. The kalsilite molecule

¹ Daly, R. A., *Eruptive Rocks*, 2nd Edn., 1943, chap. xviii; and Shand, S. J., "The present status of Daly's hypothesis of the alkaline rocks," *Am. Journ. Sci.* (Daly Volume), 1945, p. 495.

² A recent description of this important area is contained in "Alkaline and Carbonate Intrusives near Bancroft, Ontario," by F. Chayes, *Bull. Geol. Soc. Amer.*, liii (1942), p. 449.

goes into biotite, with the hydroxyl; the silica released by these reactions crystallizes as quartz, and the residual magma at this stage contains potential nepheline.

There remains for consideration another possible means of producing nepheline-syenites, again one involving carbonates and desilication, but with the rôles reversed by comparison with the Daly-Shand process. In the latter, the carbonate is the passive participant; but the field relations of some alkali-syenite complexes has led to the formulation of a hypothesis in which the carbonate participates actively in almost dramatic fashion.

Massive calcite occurs as vent intrusions in Nyassaland;¹ it forms veins and dykes, for example, in the Fen area in Norway; and cone-sheets concentrically disposed about a central plug-like boss at Alno, Sweden. In these and other areas in Central and East Africa the intrusive carbonate-rocks or **carbonatites** are so closely associated with crystalline silicate rocks as to prove community of origin. Much discussion has centred round the problem of origin of these rocks, and of the genetic relationship between the carbonate rocks and those of igneous aspect with which they are associated. At Fen and Alno the country rocks are Archaean gneisses; there is no limestone available for assimilation. At Alno in particular, according to one interpretation of the evidence, the carbonatites were produced by differentiation of a magma initially rich in alkalies and dissolved CO₂ and other volatiles. These at times exerted sufficient pressure to cause fracturing of the country-rock around the magma column, to form suites of carbonatite cone-sheets, initially dolomitic, but later becoming calcitic. Concurrently with the magmatic differentiation, solutions and gases including CO₂ reacted with the surrounding gneisses, producing zones of decreasing metasomatism concentric with the carbonatite centre. One of the chief effects was desilication which produced metasomatic syenites termed **fenites**. Nearer to the centre of activity nepheline-syenite magma was ultimately produced which, by normal processes of differentiation gave rise to a series of rock-types varying widely in composition, from nepheline-leucosyenites to ultramafites. Some of these, including porphyritic microfoyaïtes, occur in radially disposed dykes.

THE MICROSYENITES

The microsyenites are the medium-grained equivalents of the syenites on the one hand and the trachytes on the other. They are

¹ Dixey, F., Campbell Smith, W., and Bisset, C. B., "The Chilwa Series of Southern Nyasaland," *Geol. Surv. Nyasaland, Bull.* 5, 1937.

² Eckermann, H. von, "The Alkaline District of Alno Island," *Sveriges Geol. Undersök.*, 1948, Ser. Ca., No. 36; also *Min. Mag.*, xxix (1950), p. 308.

not common rocks, and in this respect are less important than either of the other grain-size groups. Several alternative names have been applied to them in the past, some of general significance, others with more specific meaning. As most of these rocks are porphyritic, with more or less prominent phenocrysts of orthoclase, they have been collectively grouped as "porphyries" (as distinct from "quartz-porphyries," which are Acid rocks of the same status, but of granitic composition, of course). In a former edition of this book we used "microsyenite" for aphyric types, and "syenite-porphyry" for those with phenocrysts. It seems better to call all these rocks, regardless of texture, by one name, and by analogy with the granitic rocks, **microsyenite** seems the obvious choice. The two textural variants are then "aphyric microsyenites" and "porphyritic microsyenites," the meanings of which are self-evident.

As regards mode of occurrence, these rocks are intrusive; but the mere fact that a syenitic rock occurs as a sill or dyke does not automatically entitle it to the name microsyenite. The latter should only be used if the rock is of medium grain; if of fine grain, it must be termed trachyte, if preferred with the prefix "intrusive" to remove any possible doubt.

Certain of these rocks are definitely potassic, and differ from the corresponding syenitic and trachytic types only in grain size. **Potassic microsyenites** often have a distinctive texture referred to as orthophyric, in effect a coarser trachytic texture resulting from the close packing of short stout prisms of orthoclase. Orthoclase is the dominant mineral, often occurring in two generations, and accompanied by hornblende, biotite, and in the more acid examples, by a little interstitial quartz. A particularly good example of a porphyritic potassic microsyenite occurs at Goodsprings, Nevada, and is noteworthy for the beautiful phenocrysts of reddish orthoclase crystals, of simple form, for which it is famous. The perfect crystals from this rock are to be found in all good teaching collections. The groundmass also consists chiefly of orthoclase, and the amount of coloured minerals is small, as in most syenitic rocks.

If the magma from which these potassic microsyenites were formed became desilicated, leucite might crystallize at high temperature, but on account of the slow loss of heat under intrusive conditions, it would invert into pseudoleucite, with falling temperature, and the rock would contain pseudoleucite and orthoclase, the proportions depending upon the degree of under-saturation achieved, accompanied by coloured silicates of the appropriate composition. Such a rock would be exactly analogous with pseudoleucite-syenite on the one hand and leucitophyre on the other and forms the connecting link between these two types. It is equally

rare; but occurrences have been noted at Magnet Cove, Arkansas, and elsewhere.

Sodic microsyenites compare closely with corresponding coarse-grained rocks, with which they are intimately associated in the field, either as marginal phases, or as dykes and sills. Provided the general principle of naming such relatively finer grained facies of distinctive plutonites after the latter as explained above (p. 231) is accepted, a clearer picture is evoked by using such specific names as microlarvikite and microfoyaite, for example, and further description is scarcely necessary. Unfortunately even to-day names are applied to such rocks which give no indication whatever of their relationship to other named parental types. Thus in a recent revision of the classic Oslo petrographic province, the relatively finer grained larvikites are called akerites.

The Oslo district also is famous for its "rhomb-porphyrries,"¹ so named by von Buch (1870) on account of the distinctive shape of the cross-sections of the feldspar phenocrysts. These rocks occur as lava-flows and dykes, and, although some are definitely fine-grained, most measured specimens lie just over the boundary between fine and medium, and are therefore appropriately considered here. Further, the composition of the rocks varies widely: some are monzonitic; but others, with a very low content of An (less than 1 per cent in extreme cases), are clearly microsyenitic. The phenocrysts are antiperthitic, the dominant partner being oligoclase or andesine, rimmed with and veined by "anorthoclase" to the extent of 30 to 50 per cent of the whole. The groundmass feldspars are microlites of anorthoclase, approximately $\text{Ab}_{32}\text{Or}_{43}\text{An}_3$. In mineral composition, therefore, rhomb-porphyrries must closely resemble larvikites, with which they are presumably consanguineous. We consider "porphyritic microlarvikite" to be an appropriate name for them.

Under-saturated types of microsyenites are well exemplified by the **microfoyaite** type, which is the mineralogical equivalent of foyaite, in the medium grain-size group. The essential components are therefore alkali-feldspar and nepheline associated with such minerals as aegirine, aegirine-augite or riebeckite. These mineral names may be prefixed to the rock name to give added precision. Riebeckite-microfoyaite grades into the commonest type of phonolite as the grain becomes finer; aegirine-microfoyaite similarly grades into typical tinguaitite. Shand has employed "microfoyaite" to distinguish certain fine-grained facies of foyaite occurring in the alkali-complexes of

¹ Oftedahl, C., "Studies on the Igneous Rock Complex of the Oslo Region. vi. On Akerites, . . . and Rhomb-Porphyrries," *Skr. utg. av Det Norske Vidensk.-Akad. Oslo.*, 1946, No. 1, p. 37.

Spitzkop and Pilaansberg in South Africa. This precedent may well be followed, without rigid adherence to a fixed limit of grain size: the thing that matters is that there is an appreciable difference in texture between the parent rock and the facies which it is desired to indicate as something different.

SYENITE APLITES AND PEGMATITES

Syenites are rare rocks, of very limited distribution. It follows therefore that syenitic rocks analogous with the granite-pegmatites already considered, will be very uncommon. They do occur, however, particularly in S. Norway where they are important on account of the rare minerals some of them contain.

In regard to syenite-aplites, bearing in mind the nature of the syenites, and the improbability of there being extensive bodies of syenitic magma, it follows that the alkali-rich residua, comparable with granitic aplites, must be exceedingly rare. Further, as syenites themselves are notably leucocratic rocks, it must prove very difficult to be certain that a given rock, suspected of being a syenite-aplite, is really such, and not merely a fine-grained facies of a normal syenite. The **bostonites**, named by Rosenbusch (1882) from Boston, Mass., are fine-grained rocks, occurring as dykes, and closely resembling trachytes in appearance. Mineralogically and texturally these rocks are leucocratic microsyenites or intrusive trachytes as the case may be. If the relations of these dyke-rocks to the parent mass are the same as those obtaining between granite-aplite and granite, then they are syenite-aplites; and if they match the type bostonites in the details of their mineral contents and texture, then they are syenite-aplites of the Boston type, or bostonites.

THE TRACHYTES AND RELATED TYPES

The fine-grained members of the alkali series of rocks of Intermediate composition are the trachytes, which thus correspond in mineral content with the syenites. The name trachyte was first applied to all volcanic rocks that, on account of vesicularity, were rough to the touch. Later the term was restricted, first to lavas of Intermediate composition, and later to those containing dominant alkali-feldspar. Trachytes are readily divided into three groups on the silica-saturation principle: (*a*) those containing free silica—the quartz-trachytes; (*b*) those which are exactly saturated, containing neither quartz nor feldspathoid—the ortho-trachytes; and (*c*) those which contain an unsaturated mineral of felsic type, including nepheline, leucite and other feldspathoids.

(a) *Quartz-trachytes and Orthotrachytes.*

Repetition is prevented by describing these two categories together: the sole difference is the occurrence of accessory quartz in the former. In theory, the same degree of latitude is allowed as for the syenites: quartz may occur up to 10 per cent of the whole rock. It never occurs as phenocrysts, but is restricted to the groundmass, where it may occur as interstitial grains lying between the feldspar microlites, or it may form micropoikilitic patches, optically continuous over an area which may include parts of a number of feldspar microlites: in other words, the quartz forms little "lakes" in the slide into which the ends of a number of microlites of feldspar may penetrate. Thus in so far as the mere names of the component minerals are concerned, there is nothing to choose between quartz-trachyte and rhyolite. Actually the amount of quartz in the former is much smaller than in an average specimen of the latter, while texturally they are very different. Although a little glass may be present, trachytes are not notably vitreous. Most trachytes are porphyritic, with phenocrysts of feldspar, often of large size. The groundmass is typically microlitic: *i.e.*, it consists of closely packed microlites, lath-like in shape, and several times longer than they are broad. On account of flow movements in the magma they are often in parallel alignment. At its best, therefore, the *trachytic texture* involves a close packing of feldspar microlites which often exhibit flow structure (Fig. 101). The amount of coloured silicates in trachytes is small: they are therefore light, both in colour and weight.

In some instances it is possible to subdivide further, on the basis of the dominant alkali, and to classify the rock as a potassic or a sodic trachyte respectively. In the former, the feldspar is sanidine, ideally, and is accompanied by ordinary biotite, clino-pyroxene or hornblende. In the latter the feldspar may be albite, but is commonly a sodi-potassic type, while the coloured silicates are the distinctively coloured soda-iron amphiboles and pyroxenes, already noted in the syenites of comparable type: *viz.*, aegirine, riebeckite, cossyrite, etc. It is important, however, to note that in some trachytes while the feldspar is dominantly potassic, the coloured minerals may be strongly sodic. Thus one such rock has been described consisting of nearly 90 per cent of sanidine, the rest consisting of aegirine and accessories. Thus although the rock is an aegirine-trachyte, it is not a sodic type, but potassi-sodic. It is customary to prefix the rock-name with that of the coloured mineral, and to speak of biotite-trachyte, hornblende-trachyte, aegirine-trachyte, riebeckite-trachyte, etc.

The Drachenfels trachyte enjoys the reputation, among trachytes of the Dresden syenite among the syenites; but like the latter it is



FIG. 101.

Trachyte, Solfatara, Naples. The principal phenocrysts are of sanidine, often forming large crystals. Oligoclase also occurs in less abundance. The groundmass is almost wholly composed of sanidine laths, though sparse interstitial patches of isotropic glass occur. Coloured minerals include pale brown hornblende, and greenish augite, sometimes in poikilitic plates (not shown).

not an ideal type—it contains a good deal more oligoclase than a typical trachyte should. It is noteworthy for the extremely large size of the sanidine phenocrysts, which measure over an inch in diameter. Much smaller plagioclases also occur, embedded in a light cream-coloured matrix.

A more typical trachyte is illustrated in Fig. 101 which represents a rock of this type from the Solfatara volcano near Naples.

Trachytes occur in the closest association with basalts, not only in recent lava fields, but also in those of earlier geological periods. Thus among the Ordovician volcanic rocks in North and South Wales, and those of Devonian and Carboniferous age in Devon and Cornwall, trachytic rocks occur, occasionally as lava flows, but more commonly as minor intrusions. As a rule in these ancient eruptives the coloured minerals are so much altered that it is impossible to state their original nature. They are often somewhat over-saturated, and while in many the feldspar is pure albite, in some it is a strongly sodi-potassic type. In this country it is customary to refer to these albitic trachytes as **keratophyres**, particularly when the associated basic lavas are also albitic—the so-called spilites.

Equally strongly sodic trachytes, probably of Carboniferous age, occur in the Eildon Hills near Melrose, southern Scotland.¹ These, however, are in a much better state of preservation, and contain the sodic amphibole, riebeckite, in the characteristic "mossy" aggregates. From the Tertiary volcano of Mull,² a similar trachyte occurs, but contains approximately equal amounts of aegirine-augite and riebeckite.

A wide variety of trachytic rocks have been described from the neighbourhood of Mt. Kenya, Kenya Colony.³ In the direction of increasing acidity they grade into sodic rhyolites, and in the other, with the incoming of nepheline, into phonolites. They closely resemble the suite described by H. S. Washington from Pantelleria, near Sicily,⁴ particularly in containing the rare sodic amphibole, cossyrite. Those rocks to which the name pantellerite was originally applied are apparently thoroughly acid (with silica percentage up to 70), and are distinctive by virtue of the occurrence of phenocrysts of anorthoclase and cossyrite, usually associated with pyroxenes. Some contain quartz phenocrysts, and are evidently sodic rhyolites, of special type; but in others quartz is no more than accessory, and the groundmass is trachytic. Such rocks, both in the type-locality and in Kenya, are aptly called **pantelleritic trachytes**. As a point of detail it may be noted that the quartz-free members of this Central African suite contain small amounts of olivine. This is also true of the

¹ Lady M'Robert, *Quar. Journ. Geol. Soc.*, lxx (1914), p. 303.

² "Tertiary and Post-Tertiary Geology of Mull," *Mem. Geol. Surv.*, Scotland, 1924, p. 191.

³ Campbell Smith, W., "A Classification of some Rhyolites, Trachytes and Phonolites from part of Kenya Colony," *Quar. Journ. Geol. Soc.*, lxxxviii (1931), p. 212.

⁴ "The Volcano and Rocks of Pantelleria," *Journ. Geol.*, xxi (1913), p. 683; and xxii (1914), p. 16.

trachytes which occur in the puy^s of Auvergne: S. J. Shand¹ has shown that the well-known rocks from Mt. Doré contain about 2 per cent of this mineral, which is a rare constituent of coarse-grained rocks of like composition.

White-weathering trachytes contrast spectacularly with the finely exposed modern basalts of the oceanic islands such as Ascension in the South Atlantic. There is little doubt that in Carboniferous times the Midland Valley of Scotland must have presented much the same aspect. In what has survived of this lava-field trachytes form occasional flows, but more commonly occur as minor intrusions and vent infillings, due doubtless to the high viscosity of the magma. This is true not only of this lava-field, but also of those elsewhere and of other ages. Further, many of these rocks exhibit some degree, usually slight, of under-saturation, and are therefore considered below.

As a consequence of their close association with basalts in the field, it is inferred that both trachytes and basalts were derived from a common magmatic source: in fact, trachytes are regarded by many as being the ultimate products of differentiation of a world-enveloping basaltic magma.

(b) *Under-saturated Trachytes: Phonolites and Leucitophyres.*

Phonolites are the fine-grained equivalents of the nepheline-syenites, and therefore consist essentially of nepheline, alkali-feldspar, usually sanidine, and a ferromagnesian mineral which may be aegirine, aegirine-augite, arfvedsonite or riebeckite, and rarely cossyrite. The presence of nepheline should be suspected in any rock carrying these sodic amphiboles and pyroxenes, and careful search will usually reveal the characteristic tiny square or six-sided sections (Fig. 102). When the nepheline is interstitial to the feldspar, however, it may prove very elusive, and a staining test is called for.

In hand-specimens phonolites are very compact, grey-green rocks which are supposed to give a sonorous ring when struck by a hammer—hence their name, which is a classical rendering of an old term, "clinkstone," used by A. G. Werner with the same significance. Texturally most phonolites are porphyritic, the phenocrysts including both nepheline and sanidine. A very well-known example which is found in most teaching collections is figured below.

The quantity of nepheline in phonolites is very variable, and it is clearly necessary to distinguish between those in which the mineral has the status of an essential component, and those in which it is an accessory only. The latter are the connecting links between the true phonolites and the true saturated trachytes. In the sense that they

¹ *Geol. Mag.*, 1935, p. 86.

consist of the minerals appropriate to trachyte, with nepheline in addition, the logical name for them is nepheline-trachyte; but as Johanssen and others unfortunately have already used this term in another sense, the alternative of **phonolitic trachyte** may be used. An example familiar to British petrologists forms the Traprain Law Laccolith in Haddington, Scotland. The greater part of this rock consists of fluxionally arranged laths of alkali-feldspar, and the



FIG. 102

Phonolite, Brux, Bohemia. Both sanidine and nepheline occur in crystals of two generations. The former shows alteration parallel to the basal cleavage. The latter forms almost square or hexagonal sections, outlined in some cases by dark poikilitic riebeckite aggregates.

nepheline, which only amounts to 4 per cent, is elusive in thin sections; but it is supported, as it were, by 20 per cent of analcite and a few grains of sodalite.¹ Strictly the Traprain Law rock is a sodalite-bearing phonolitic analcite-trachyte.

Even closer to trachyte is a similar rock which forms a plug, known as the Bass Rock in the Firth of Forth, Scotland. Soda-orthoclase makes up 85 per cent of the rock, nepheline, sodalite and analcite all occur, but only in very small amounts, about 1 per cent

¹ Macgregor, A. G., *Geol. Mag.*, lix (1922), p. 514.

while the coloured silicates are aegirine-augite and fayalite, totalling some 8 per cent.

The phonolite which forms the Wolf Rock off the Cornish coast is much more typical than these Scottish rocks. In addition to nepheline it contains much greyish nosean, and the term **nosean-phonolite** is applicable. Similarly, **sodalite-phonolite** contains all the minerals of typical phonolite, but in addition sufficient sodalite to be regarded as an essential constituent. The volcanic tract in Turkana, Kenya,¹ has provided a good example—a dense fine-grained green rock, which under the microscope is seen to be composed chiefly of laths of orthoclase (sanidine), grains of aegirine and small poikilitic patches of sodic amphibole, together with abundant though small (0.025 mm.) euhedral sodalites. The rock is, of course, the fine-grained equivalent of sodalite-syenite.

By analogy, **leucite-phonolite** should contain the minerals of true phonolite, with leucite in addition. The rocks of the Roman volcanic province provide examples. Leucite and aegirine-augite occur as phenocrysts, while the groundmass consists of soda-orthoclase, nepheline, aegirine-augite and sometimes sky-blue hauyne. With increasing leucite and decreasing nepheline, leucite-phonolite grades into leucitophyre, which typically contains no nepheline.

Of rather special interest are the basic, phonolitic trachytes of Kenya type, named **Kenyte** by J. W. Gregory,² from the type-locality, Mt. Kenya, Kenya Colony, but known to occur also at Mount Erebus, Antarctica.³ The distinctive feature is the nature of the feldspar which occurs as large prisms, rhombic in cross-section, of anorthoclase. In shape, if not in composition, these appear to be identical with the feldspars of rhombic cross-section occurring in the Oslo larvikites and rhomb-porphyrries. In this and other respects, both chemical and mineralogical—the occurrence of small quantities of olivine and nepheline⁴—kenyte closely resembles larvikite and laurdalite, and it is undoubtedly their fine-grained equivalent. Rhomb-porphyry is the medium- to fine-grained dyke-equivalent, and, as might be expected, occurs in association with the kenytes on Mt. Kenya.

Closely similar to phonolites and certainly falling in the same grain-size group are the **tinguaites** (Rosenbusch, 1887), named from the Tinguá Mountains, near Rio de Janeiro, Brazil. They are

¹ Campbell Smith, W., *Quar. Journ. Geol. Soc.*, xciv (1938), p. 522.

² Redescribed by W. Campbell Smith in *Bull. British Museum (Nat. Hist.)*, Vol. I, No. 1, p. 3.

³ Prior, G. T., "National Antarctic Expedition, 1901-04," *Nat. Hist.* 1907, i, p. 101.

⁴ Campbell Smith, W., "Classification of some Rhyolites, Trachytes and Phonolites from part of Kenya Colony," *Quar. Journ. Geol. Soc.*, lxxxvii (1931), p. 242.

identical with phonolites in composition and occur in dykes and as marginal facies of nepheline-syenites. Consisting essentially of alkali-feldspars and nepheline, with a moderate amount of aegirine, the difference between phonolite and tinguaitite is essentially textural (Fig. 103). In phonolites the coloured mineral commonly occurs in small patches poikilitic towards the sanidine laths and squares and hexagons of nepheline; it is sometimes riebeckite in "mossy" patches.

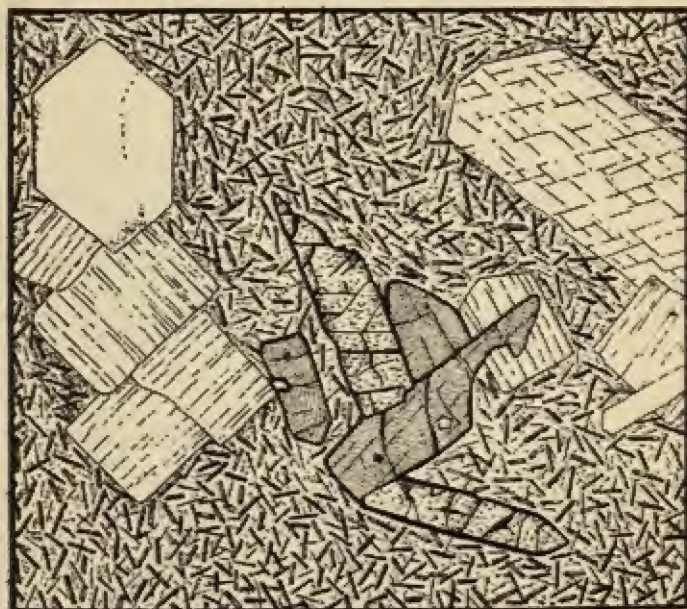


FIG. 103

A K W.

Porphyritic tinguaitite, Brazil. Phenocrysts of nepheline (with basal cleavage); sanidine, brilliant green aegirine, and sphene, set in a groundmass in which minute aegirine microlites are abundant.

In tinguaites the coloured mineral is aegirine, in acicular crystals, uniformly distributed and lying parallel to the sides of the felsic constituents. With increasing grain-size tinguaites grade through aegirine-microfoyaïtes into foyaïtes.

Leucitophyres.

Obviously the fine-grained rocks consisting essentially of the combination leucite-alkali-feldspar-coloured minerals, have the same status as phonolite, and require a distinctive name. We select leucitophyre for this purpose, although it is not ideal, having been used previously in more than one sense. As used by Rosenbusch, for

example, the term implied the presence of both leucite and nepheline, together with sanidine. According to our definition, Rosenbusch's leucitophyre is nepheline-leucitophyre, intermediate in its mineral contents between true leucitophyre and phonolite, but definitely nearer to the former than to the latter. The best known rock of this



FIG. 104

Nosean-leucitophyre, Rieden, Eifel. Megaphenocrysts of leucite and nosean are about equally abundant, occurring with green-rimmed sodic pyroxene, set in a groundmass of sanidine and minute euhedral nepheline crystals. Apatite and sphene are important accessories.

type occurs as a dyke near Rieden in the Eifel. In the hand-specimen numbers of small phenocrysts of leucite and nosean are plentifully scattered in a greyish groundmass which also contains small black prisms of pyroxene. Under the microscope the phenocrysts of leucite and corroded noseans with heavy black borders are very

striking (Figs. 48 and 104). Small nephelines of typical shape occur in the groundmass only, where they are associated with equally small laths of sanidine. Aegirine-augite is abundant, while sphene, apatite, magnetite, and less commonly melanite garnet, are usual accessories. The proper designation of this well-known rock is nosean-nepheline-leucitophyre. The chemical composition is stated in the table of analyses, p. 256.

Leucitophyres occur together with other related types in the Leucite Hills, Wyoming. One variety¹ consists of equal amounts of leucite, sanidine and coloured minerals. Among the latter, phlogopite, a rare mineral in normal igneous rocks, is dominant, forming small phenocrysts visible in the hand-specimen. It is accompanied by minute needles of diopside and a kataphorite-like amphibole. This is a type of **phlogopite-leucitophyre**, and for its silica percentage is particularly rich in potash.

Two associated lava-types present a problem in classification and nomenclature. The first again contains leucite and phlogopite as its essential components, and it is therefore closely related to the phlogopite-leucitophyre noted above; but as it contains no feldspar, it may be excluded from the leucitophyres, though actually the groundmass is partly glassy, and there is little doubt that, had crystallization been completed, sanidine would have appeared. Thus the feldspar is occult, and the rock, termed **Wyomingite** by Cross² may legitimately be considered here, in spite of its technical failure to conform to the definition of leucitophyre. Wyomingite is a partially glassy potential phlogopite-leucitophyre.

The third type established by Cross from this locality is a basic rock and is described in due course.

Hauynophyres.

Theoretically the fine-grained type, normally occurring as lava-flows and characterized by the assemblage hauyne-sanidine-coloured minerals should be distinguished as hauynophyre. With the incoming of leucite, hauynophyre grades through leucite-hauynophyre into leucitophyre; and with the incoming of nepheline in increasing amounts it grades into phonolite *via* the intermediate type, nepheline-hauynophyre.

(b) THE DIORITE CLAN

The predominance of alkali-feldspar or feldspathoids makes it relatively easy to define and classify the syenitic rocks; but the

¹ Termed "orendite" by W. Cross, "Igneous Rocks of the Leucite Hills and Pilot Butte, Wyoming," *Amer. Journ. Sci.*, iv (1897), pp. 126, 134 and 139.

² *Op. cit. supra.*, pp. 120, 131, and 137.

ANALYSES OF TRACHYTES, PHONOLITES AND LEUCITOPHYRES

	I. Sodic trachyte, Ardnacross.	II. Olivine sodic trachyte, Mt. Doré, Auvergne.	III. Trachyte, Peppercraig.	IV. Kenyite, Mt. Kenya.	V. Trachytoid Phonolite (Intrusive), Traprain Law.	VI. Phonolite, Kenya Colony.	VII. Leucitophyre, Leucite Hills.	VIII. Leucitophyre, Rieden.
SiO ₂	60.13	55.20	62.61	53.98	56.89	58.37	53.70	55.18
Al ₂ O ₃	16.53	15.65	18.17	19.43	19.11	16.65	11.16	23.03
Fe ₂ O ₃	2.86	2.86	0.32	4.39	2.04	4.09	3.10	2.85
FeO	3.01	4.59	4.25	2.05	3.64	3.03	1.21	n.d.
CaO	1.20	3.95	2.58	1.07	2.16	0.37	6.44	1.06
MgO	1.72	6.38	0.74	2.04	0.35	1.66	3.46	0.25
Na ₂ O	8.06	5.27	6.49	8.81	6.35	7.28	1.67	5.98
K ₂ O	3.99	4.12	4.02	5.27	6.88	5.46	11.16	8.43
H ₂ O	1.52	0.45	0.80	1.79	2.22	2.36	3.41	2.62
TiO ₂	0.73	2.26	—	0.57	0.32	0.21	1.92	n.d.
Other constituents.	0.57	0.15	0.20	0.56	0.54	0.51	3.17	0.76
	100.32	100.88	100.18	99.96	100.50	99.99	100.40	100.16

I. Sodic trachyte (Plug), Ardnacross, Mull (Anal. E. G. Radley). Mull, *Mem. Geol. Surv.*, 1924, p. 27.

II. Olivine sodic trachyte, Mount Doré, Auvergne (P. G. Söhngen).

III. Trachyte, Peppercraig, Haddingtonshire (J. Grant Wilson).

IV. Kenyite, the type-rock, Mount Kenya (Anal. G. T. Prior), quoted from W. Campbell Smith, *op. cit.*, p. 246.

V. Intrusive "Trachytoid Phonolite," Traprain Law, Haddingtonshire, Scotland (Anal. F. R. Ennos), *Geol. Mag.*, lix (1922), pp. 514-523.

VI. Phonolite, Kenya (Anal. G. T. Prior), *Q.J.G.S.*, 1931, p. 264.

VII. Leucitophyre, Wyoming type, Leucite Hills, Wyoming (Anal. W. F. Hillebrand).

VIII. Leucitophyre, Rieden, Laacher See, Eifel (Anal. K. Busz).

case is different with the members of the Diorite Clan, and much difficulty has been experienced in separating diorites from gabbros on the one hand, and andesites from basalts on the other. At different times and by different authorities the division has been made on the basis of the following criteria: (i) silica percentage; (ii) nature of the coloured minerals; (iii) kind of plagioclase present; and (iv) the percentage of coloured minerals—the colour index of the rock. Undoubtedly the easiest way of effecting the separation is to choose arbitrarily a convenient silica percentage, regardless of other considerations. This principle has already been discussed and found wanting; and for reasons already stated, we prefer to define these rock-types in terms of their constituent mineral assemblages. Firstly, as regards the kinds of coloured silicates in diorites and gabbros, in all but the earliest attempts at classification, it has been tacitly agreed that the combination hornblende-plagioclase is characteristic of dioritic and andesitic rocks. Both Zirkel and Rosenbusch were agreed on this point. Secondly, most petrologists agree that the occurrence of olivine as a normal constituent indicates gabbro and basalt, rather than diorite and andesite. The position when pyroxene is concerned is less clear. A clinopyroxene is certainly the most common and characteristic mafic mineral in typical gabbros and basalts; but a member of this mineral group is common also in trachytic and even rhyolitic lavas and pitchstones, and in the intermediate andesitic rocks pyroxene is bound to be an important constituent. The problem, therefore, is to separate pyroxene-andesites from (pyroxene) basalts, and augite-diorites from (augite) gabbros. Two criteria are available: (a) the quality of the plagioclase or (b) the colour index may be used. The nature of the feldspar-content has already been given an important rôle in rock classification, and it is merely an extension of this principle to use it in the present case. The division is purely arbitrary, and is that favoured by Johanssen and many other American petrologists. In typical gabbros the plagioclase varies between labradorite and bytownite; in diorites it commonly lies within the oligoclase-andesine range. Logically the division should therefore be drawn at the andesine-labradorite boundary, *i.e.*, at An_{50} . The acceptance of this principle involves the accurate determination of the composition of the plagioclase before the rock can be accurately named. Zoning introduces some difficulty, of course, and in the fine-grained rocks it may be almost impossible to apply the principle, except on the basis of normative as distinct from modal plagioclase.

As regards colour index, the determination of this factor is a much less highly-skilled operation, particularly when one is dealing with coarse-grained rocks, and is therefore a more appropriate basis

of classification for students. This is the basis favoured by Shand, who advocates drawing the line between diorite and gabbro and the corresponding fine-grained types, at a colour index of 30. It has been shown by S. E. Ellis¹ that many typical diorites have a higher colour index than this, and 40 appears to agree more closely with the natural boundary between the two classes.

The position reached, then, is this. No single criterion will serve

TABLE SHOWING THE GENERAL RELATIONSHIP BETWEEN
THE DIORITIC AND GABBROIC ROCKS

	Ab ₁₀₀ An ₀	Ab ₅₀ An ₅₀	Ab ₀ An ₁₀₀
	100		
COLOUR INDEX		HORNBLENDITES	PYROXENITES
	90		
		MELADIORITES	MELAGABBROS, ETC. GABBROS, NORITES, EUCRITES, ETC.
	40		
		DIORITES LEUCODIORITES	LEUCOGABBROS, LEUCONORITES, ETC.
	10		
		OLIGOCLASITE ANDESINITE	ANORTHOSITE

satisfactorily to separate diorite from gabbro, and andesite from basalt; but satisfactory definitions can be made on the basis of colour index, composition of the plagioclase, and kind or kinds of mafic minerals present. The general characters of the rocks of the Diorite Clan are summarized as follows:

¹ *Min. Mag.*, xxviii (1948), p. 447. By means of a careful statistical study, Ellis has examined this problem, and has shown that a colour index of 40, and in the plagioclase, an An-content of rather less than 50, are the most suitable values to use. We prefer drawing the line at An₅₀, however, as this value separates andesine from labradorite.

(i) these rocks are essentially combinations of plagioclase feldspar and coloured silicates, excluding olivine, but including typically hornblende, with biotite in the more acid, and pyroxene in the more basic members;

(ii) plagioclase must make up at least two-thirds of the total feldspar content; it should be not more calcic than An_{30} ;

(iii) the colour index should not exceed 40;

(iv) quartz is typically absent; if present it must rank as an accessory mineral only, and in any case must not exceed 10 per cent. Really typical diorites will conform to the whole of this specification; but rocks will undoubtedly be encountered which, on the balance of evidence, must be classed as diorites, though they may not precisely conform with the definition in all the details laid down. Examples will be discussed in due course.

The three grain-size groups within the Clan are as follows:

Coarse
DIORITES

Medium
MICRODIORITES

Fine
ANDESITES

THE DIORITES

The main outlines of the definition of diorite have been laid down above. Fundamentally the type is a coarse-grained rock consisting typically of andesine and common hornblende. There is scope here for wide differences in appearance, according to the ratio of felsic to mafic minerals. The complete range of types covering *all* proportions of these components would include rocks at both ends which cannot be admitted as diorites. The typical diorite is a black and white rock, with rather less dark than light mineral; but types with less than the 40 per cent specified grade with diminishing dark mineral content into feldspar-rich types (*leucodiorites*), and ultimately into rocks consisting solely of plagioclase. According to whether the plagioclase is within the oligoclase or the andesine range, such rocks may be termed *oligoclasite* and *andesinite* respectively. In the sense that, apart from minor accessories, they are composed exclusively of plagioclase, they agree closely with the anorthosite type which, however, has affinities with gabbroic rocks, and is described in due course.

In the other direction increase in the colour index gives melanocratic, feldspar-poor diorites, which may well be classified as *meladiorites*. Carried to the limit, this line of variation ultimately gives ultramafic rocks of the hornblendite type. The colour index within this mineral-assemblage group is thus variable between zero and

100. The limit between meladiorite and the monomineralic hornblendite is drawn at 90, and that between leucodiorite and the monomineralic oligoclasite and andesinite at 10.

The most acid diorites contain quartz as an essential, though minor, constituent, and are distinguished as **tonalites**. With increasing quartz the latter grade into granodiorites. Both of these rock-types, therefore, contain the same mineral assemblage, but the proportions are different. In both, orthoclase is ideally absent, but often present in subordinate amounts and must not exceed one-third of the total feldspar. While the amount of quartz must not exceed 10 per cent in tonalite, it is unlimited in granodiorite. It must be pointed out here that Johanssen uses "tonalite" in a very different sense. Provided the plagioclase lies within the oligoclase-andesine range, he does not restrict the amount of quartz present. The essential feature, in his view, is the absence, or practical absence, of orthoclase. Thus many of Johanssen's tonalites are granodiorites as defined in this book. Provided the felsic minerals conform to the standard laid down, it does not seem necessary to restrict the coloured silicate; it may be hornblende, biotite or pyroxene, alone or in association.¹ In the original tonalite from Monte Tonale in the Tyrol biotite accompanies hornblende. In Britain tonalites have been described from the neighbourhood of Loch Awe, south-east of the Ben Cruachan granite.² The composition is as follows: plagioclase (An₃₀) 72, micropertthite 11, quartz 7, dark minerals and accessories 11 per cent. Similar tonalites occur elsewhere in Scotland as integral parts of the Caledonian plutonic complexes, including those of Galloway.³

The diorite illustrated in Fig. 105 represents the ideal type: it is not over-saturated, biotite is very subordinate to common green hornblende, the plagioclase, as is commonly the case, is zoned, with the cores more calcic than the outer parts of the crystals. The normal accessory minerals liable to occur in diorites of all kinds include sphene, probably the most prominent, apatite and magnetite. In the more basic diorites the place of hornblende tends to be taken by either a clinopyroxene which is colourless in thin section, or by an orthopyroxene, usually identified as hypersthene. As regards texture, diorites and tonalites in the great majority of cases are like ordinary granites—hypidiomorphic granular. Most teaching

¹ Cf. Bailey, E. B., who in the "Geology of Glencoe and Ben Nevis," *Mem. Geol. Surv.*, 1916, p. 159, restricts tonalite to quartz-diorites containing hornblende and biotite.

² Nockolds, S. R., "The Contaminated Tonalites of Loch Awe," *Quar. Journ. Geol. Soc.*, xc (1934), p. 302.

³ Gardiner, C. I., and Reynolds, S. H., "The Loch Dee Complex," *Quar. Journ. Geol. Soc.*, lxxxviii (1932), p. 1.

collections contain specimens of "corsite" or "napoleonite," the best known orbicular rock, which until recently has been classified as orbicular diorite; but in view of its thoroughly basic character—it contains only 46 per cent of SiO_2 —and the calcic nature of the plagioclase, which is bytownite (An_{73-83}), in recent accounts it has

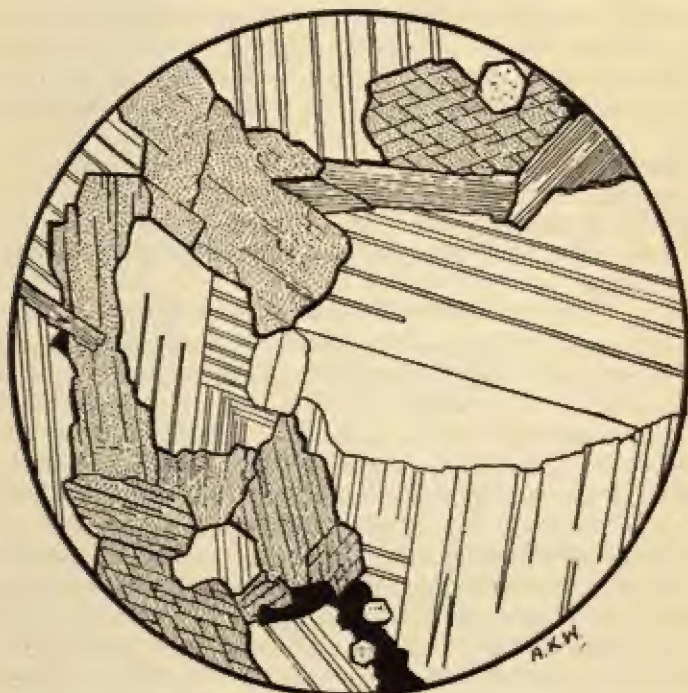


FIG. 105

Biotite-hornblende-diorite, Haute Savoie, France.

Plagioclase, common hornblende, biotite, magnetite and apatite shown. Drawn in plane polarized light, but the twinning of the plagioclase is indicated.

been transferred to the gabbros. This is a difficult case. In respect of its coloured mineral (almost exclusively hornblende) and its low colour index (21) it is dioritic; but in respect of its feldspar and its chemical characters it is much more gabbroic than dioritic. The orbs make up about half the rock and consist of alternate shells of bytownite and amphibole of a somewhat bladed habit. The matrix is normal.

Meladiorites differ from normal diorites only in their higher content of dark minerals. Examples have been described from the

Glen Fyne-Garabal Hill complex in south-western Scotland; and they occur also in Jersey, Channel Islands. Some of the rocks described in Survey Memoirs as **appinites**¹ are hornblende-meladiorites, and belong here. The hornblendes occur in the form of long-bladed crystals, and include not only common green hornblende, but also the brown or greenish-brown variety, lamprobolite. With increasing hornblende they grade into the ultramafic hornblendites.²

A complex which has many points in common with the Garabal Hill intrusion occurs at Cortlandt, New York State, and one member of the complex is a good example of meladiorite. The colour index is 54; the plagioclase, making up 46 per cent of the rock, is oligoclase-andesine; while biotite (32 per cent) is the most abundant mafic mineral, common hornblende (8 per cent) and the usual accessories making up the remainder. In spite of its low silica percentage (42·5) it would be inappropriate to classify this rock otherwise than as a meladiorite.

Dioritic rocks of unusual composition include **plumasite**, described by Lawson (1901) from Plumas County, California. The type-rock forms a wide dyke cutting peridotite, and is fundamentally an oligoclase-corundum rock. The corundums are light-bluish in colour, up to an inch in length, and are embedded in a matrix of white oligoclase. More recently very similar plumasites have been described from Natal and the Transvaal, South Africa, where again they form dykes, and tend to be of pegmatitic facies—the corundums may be several inches in length. The marginal facies of these African rocks may be almost pure oligoclase, while the corundum becomes an important constituent in the more central parts.

Only slightly different from plumasite is the so-called **dunganonite** (Adams and Barlow, 1900)³ described from Dungannon in the Haliburton-Bancroft area in Ontario, a locality well-known for its nepheline-syenites. Dunganonite is, in effect, a plumasite with a rather more calcic plagioclase taking the place of oligoclase. Andesine makes up about three-quarters of the whole rock, and

¹ It should be noted that in a Survey Memoir, *apinites* are so named on the basis of richness in hornblende, *regardless of the nature of the feldspar associated with it*. We strongly dissent from this usage as a matter of principle. One rock-name cannot be applied indiscriminately to a type of syenite and to a species of diorite—it strikes at the root of the principles of differentiation between major rock-types. Either the name must refer to a melasyenite, or to a meladiorite—not to both.

² Bailey, E. B., in "Geology of Glencoe and Ben Nevis," *Mem. Geol. Surv. Scotland*, 1916, p. 168.

³ du Toit, A. L., "Plumasite . . . from Natal," *Trans. Geol. Soc. S. Africa*, xxi (1918), p. 53.

⁴ "Geology of the Haliburton-Bancroft area, Ontario," *Geol. Surv. Canada Mem.* No. 6, 1910, p. 315.

large corundums about half of the rest. White mica, often tending to sheath the corundums, biotite, and perhaps the most important accessory, nepheline, also occur in small quantities. Again, it is found that some phases of dungannonite are almost pure andesine-rocks, that is, typical andesinites. These rocks are of special interest because in the first place they are *under-saturated* diorites; and secondly, except for corundum-syenites (described above), they are the only normal igneous rocks which contain corundum. It is doubtful if both names (plumasite and dungannonite) are needed. The range of plagioclase in normal diorites is oligoclase to andesine, and therefore both could well be covered by plumasite, which has priority. Dungannonite is a nepheline-plumasite, and with increasing nepheline grades into corundum-nepheline-syenites.¹

From the petrogenetic point of view these corundum-bearing rocks are of special interest, though the problem of their origin has not yet been solved. One factor involved is demonstrably desilication; for in several instances the dyke-rocks carry quartz until they penetrate, or at least come into contact with, peridotite or serpentinite, which is the same thing chemically. At the point where quartz disappears, the wall-rock shows a gain in silica, and corundum appears in the dyke-rock. But the loss of silica by the dyke-rock is not the only factor involved as there is a considerable gain in alumina to be accounted for. Those who have made a special study of certain Russian corundum-bearing rocks believe that the alumina was introduced by volatiles. In this connection significant evidence is afforded by a more basic rock, an anorthositic gabbro—and thus definitely not dioritic, though it may well be considered here for convenience. In certain crush-zones, the normal calcic plagioclase has been replaced by the barium-feldspar, hyalophane. Calculation has shown that the amount of free alumina (corundum) is almost exactly the difference between the combined alumina in the original labradorite (28.2 per cent) and in the hyalophane (19.5 per cent).² It is suggested that the transfer of ions was effected by volatiles, and this receives some confirmation in the occurrence of the barium-zeolite, harmotome, in cavities and on joint-surfaces. Thus in this instance, no alumina has been introduced from outside the rock—it has resulted from a redistribution of materials within it, through the agency of volatiles of unknown composition, which have removed sodium and calcium ions, and left behind potassium and barium ions.

¹ Craigmontite (Adams and Barlow, *op. cit.*, 1910, p. 311,) consists of one-third acid plagioclase; most of the rest is nepheline, while corundum is an accessory only.

² Tomlinson, W. H., "Corundum in a Dyke at Glen Riddle, Pennsylvania," *Amer. Min.*, xxiv (1939), p. 339.

The problems concerning the origin of the more normal diorites are discussed in a later chapter.

THE MICRODIORITES

The general name microdiorite has been chosen for all those rocks of dioritic composition, but of medium grain-size, that differ only in texture from the diorites into which they pass with increasing coarseness. As the grain becomes finer, they pass into the andesites. Though aphyric types are known to occur, most microdiorites are porphyritic. To cover these textural variants two general types are distinguished:—

- (i) porphyritic microdiorites; and
- (ii) aphyric microdiorites.

The former are frequently named "diorite-porphyrries," but this name has been applied to porphyritic diorites, and is better not used. A synonym which is still widely used is "porphyrites"; but again there are many objections to its use, and in view of the several quite different usages, it is highly desirable to drop this term in favour of **porphyritic microdiorite**. In textural detail many of these latter rocks closely resemble andesites, and there is no doubt that many so-called "porphyrites" are as fine grained as most andesites, and were named solely on account of their mode of occurrence as minor intrusions. Some of the "porphyrites" surrounding the Dalbeattie granite, for example, consist of a devitrified glassy matrix in which the abundant and relatively large phenocrysts are embedded. Although hypabyssal in mode of occurrence, such rocks are (intrusive) hornblende-biotite-andesites.

The nature of the dominant coloured mineral may be used for further subdivision, giving mica-microdiorite, hornblende-microdiorite, and less commonly augite- and hypersthene-microdiorites. Those specimens containing quartz (and usually biotite) are closely allied to tonalites and are to be distinguished as **microtonalites**. In such rocks the quartz is restricted to the groundmass, where it may be intergrown with orthoclase as micropegmatite. Rocks of much the same general appearance but containing quartz phenocrysts in addition to those of other minerals prove on careful examination to be dacites, and in general, this is a useful means of distinguishing between these two types. A rather special type of over-saturated porphyritic microdiorite has been named **markfieldite**, from Markfield in the Charnwood Forest area in Leicestershire. A graphic intergrowth of quartz and alkali-feldspar forms the groundmass in which numerous phenocrysts (if they are so to be

regarded) of plagioclase and hornblende are closely packed. The feldspar is red stained, and the general aspect of the rock is syenitic. An example of graphic microdiorite of a different type occurs at Penmaenmawr on the North Wales coast. In and around the Harlech Dome, also in North Wales, numerous minor intrusions, presumably of Ordovician age, occur. Many of these are of dioritic composition and some fall in the microdiorite category. They are noteworthy for the prominent phenocrysts of hornblende, plagioclase, and less commonly augite which they contain. Unfortunately they are not particularly attractive subjects for petrographic study for they have experienced a mild regional metamorphism which has, in many instances, completely pseudomorphed the original minerals: hornblende is represented by aggregates of chlorite, epidote and calcite, while the plagioclase phenocrysts are now composed of paragonite, zoisite, etc.¹

Among the many "porphyrites" of the Survey officers porphyritic microdiorites occur in the dyke swarms related to the late-Caledonian and old Red Sandstone volcanic centres in southern Scotland, for example in the Glencoe-Ben Nevis area and the Cheviot Hills. They are in a much better state of preservation than the Welsh Ordovician rocks of the same types, and include strongly porphyritic rocks with phenocrysts of biotite, common hornblende and plagioclase (Fig. 106). Many contain a little quartz, and probably microtonalite is the commonest type.

THE ANDESITES

The fine-grained members of the Diorite Clan are collectively known as andesites. The essential distinction between the latter and the microdiorites is the coarser grain of the latter, the division being drawn at the limit of unaided vision for the groundmass grains or microlites. Normally andesites thus defined occur as lava flows, but they may occur as minor intrusions, particularly dykes.

Andesites consist essentially of plagioclase within the oligoclase-andesine range, associated with one or more of the coloured silicates biotite, hornblende, clinopyroxene or orthopyroxene. It is customary to use the name of the dominant dark mineral as a prefix before the general rock-name and thus to distinguish mica-andesite, hornblende-andesite, enstatite-andesite, etc. The plagioclase phenocrysts are often quite strongly zoned. The hornblende is a brown "basaltic" variety (lamprobolite), and both it and the biotite show in the clearest manner that they were not in equilibrium with the magma

¹ Wells, A. K., "Geology of Rhobell Fawr," *Quar. Journ. Geol. Soc.*, lxxxix (1925), p. 463; and summary account by the same writer in Matley, C. A., "The Harlech Dome . . .," *Quar. Journ. Geol. Soc.*, cli (1946), p. 23.

in which they were floated up from depth: they exhibit all degrees of magmatic corrosion. At an early stage this may amount to no more than a slight "peppering" with magnetite granules, but at a later

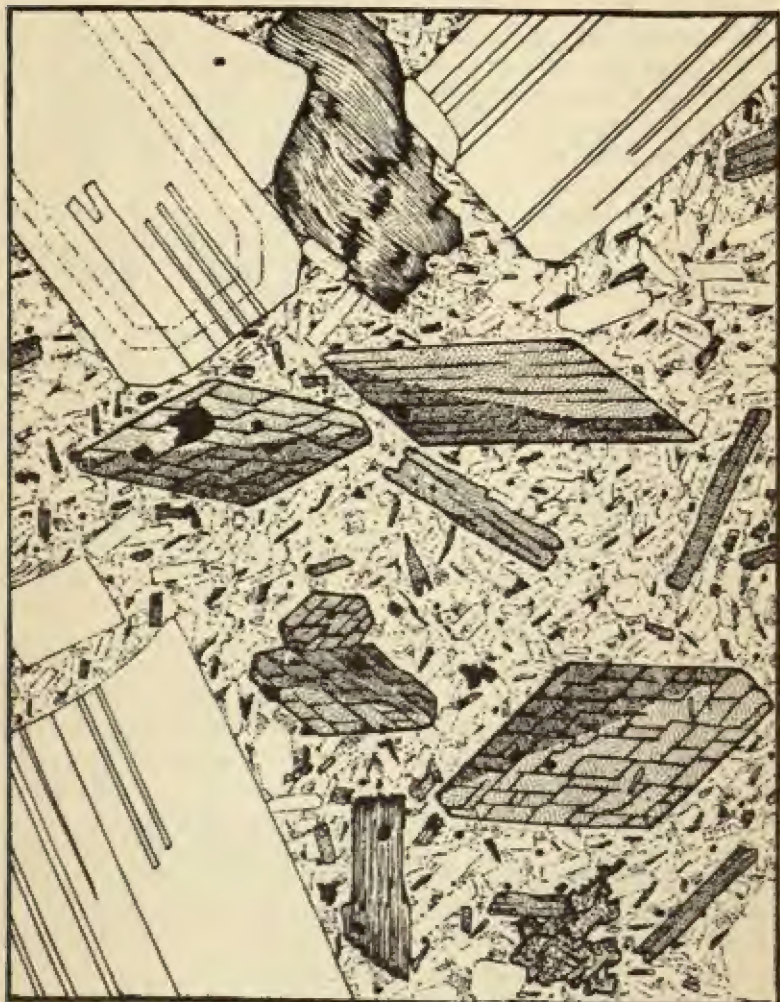


FIG. 106

A.K.W

Porphyritic microdiorite ("porphyrite"), Shore, Dalbeattie, Scotland. Euhedral plagioclase (showing twinning and zoning), common hornblende (often twinned), and biotite, all in two generations. The groundmass is microcrystalline. Accessories include sphene, magnetite and minute apatites.

ANALYSES OF TONALITES, DIORITES AND MICRODIORITES

	I. • Tonalite (Daly's average).	II. Quartz-diorite (Tonalite type), Carinthia.	III. Diorite, Daly's average.	IV. "Porphyrite," Glencoe.	V. Graphic microdiorite, Penmaenmawr type.	VI. Markfeldite (type-rock).
SiO ₂	62.35	63.09	59.67	65.30	58.45	55.7
Al ₂ O ₃	16.41	18.89	16.68	15.20	17.08	17.5
Fe ₂ O ₃	2.57	3.48	2.93	2.49	0.76	5.2
FeO	3.82	2.02	4.09	2.53	4.61	4.7
MgO	2.83	1.97	3.62	1.80	5.15	2.9
CaO	5.45	6.18	6.22	3.16	7.60	6.7
Na ₂ O	3.41	3.14	3.50	4.13	4.25	2.4
K ₂ O	2.13	1.30	2.13	3.37	1.02	2.1
H ₂ O	—	0.63	0.77	1.00	1.07	2.3
TiO ₂	0.67	—	0.39	0.83	—	—
Other constituents	0.36	—	—	0.23	—	—
	100.00	100.70	100.00	100.04	99.99	99.5

I. Tonalite, Daly's average (1933).

II. Quartz-diorite (Tonalite type), Wistra, Carinthia, Austria (W. Krezmar).

III. Daly's average diorite.

IV. Porphyritic microdiorite, Glencoe, Scotland (Anal. E. G. Radley), *Ben Nevis Memoir*, 1916, p. 183.

V. Graphic microdiorite, Penmaenmawr, North Wales (J. A. Phillips).

VI. Graphic microdiorite (Markfeld type), Markfeld, Charnwood Forest (J. H. Player).

stage of alteration the hornblende is progressively replaced by an aggregate chiefly consisting of granules of nearly colourless clinopyroxene and octahedra of magnetite (Fig. 107). In extreme cases the whole of the mica and hornblende may be so replaced, and only the shapes of the original phenocrysts survive. Finally even this is lost, and an indefinite area rather richer in augite and magnetite

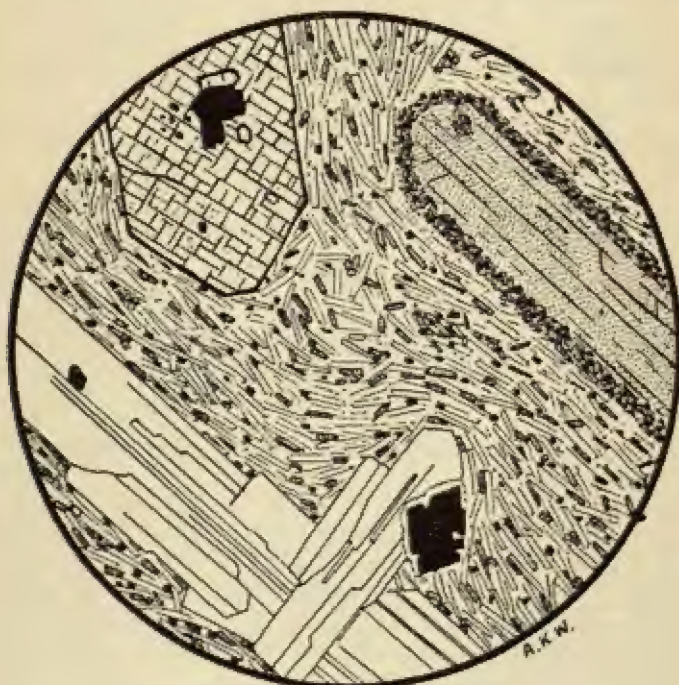


FIG. 107

Hornblende-augite-andesite, Col d'Entremont, Contal,
Auvergne.

Complex twinned plagioclase, augite, and corroded hornblende phenocrysts are embedded in a groundmass of plagioclase microlites, together with prismoids of colourless augite, and minute magnetite octahedra.

than the general body of the rock is all that remains. In the same rock phenocrysts of pale-coloured clinopyroxene may occur, and were apparently quite stable. It is worthy of note that the clinopyroxene in typical andesites is a light greenish diopsidic variety, not the common brown augite so typical of basaltic rocks. The enstatite in andesites represents the olivine of more basic lavas, and is easily distinguished by its characteristic cross section—nearly

square with the corners truncated (Fig. 108). Hypersthene is similar but in thicker sections exhibits its characteristic pleochroism. In the more ancient hypersthene-andesites the orthopyroxene is commonly replaced by the so-called bastite pseudomorphs.

The groundmass in which the phenocrysts are embedded may be wholly crystalline and composed largely of narrow microlites of



FIG. 108

Enstatite-andesite, Asama-yama, Japan.

Phenocrysts of euhedral zoned plagioclase and enstatite set in a subvitreous groundmass which contains a few skeletal feldspars.

plagioclase, associated, it may be, with granules of coloured minerals and not much iron ore (Fig. 107). If the microlites are so closely packed as to exclude glass altogether, the texture is said to be **pilotaxitic**; but in some instances wedges of glass lie between the microlites, giving the **hyalopilitic** texture. By increase in the proportion of glass to microlites such andesites grade into true andesitic glass. The latter is brown in thin section and may be perfectly transparent; but with increasing age it tends to lose its transparency through devitrification, just as with rhyolitic glass.

Andesites are somewhat prone to alteration through a variety of causes. Solfataric action in the neighbourhood of an active volcano, slight regional metamorphism or even atmospheric weathering tends to render the plagioclase turbid, to replace it by secondary albite charged with zoisite or epidote, while the coloured minerals are progressively replaced by chlorite, epidote, calcite, etc. Any vesicles in the rocks become filled with such minerals as calcite, chlorite, prehnite and other zeolites. It was to andesitic rocks in this altered condition that the name "porphyrite" was first applied. A little secondary quartz is liberated during such alteration: there is usually little doubt that it is secondary, on account of its mode of occurrence and its associates. In some andesites, however, a little primary quartz is to be expected on general grounds: the extrusive, fine-grained equivalent of tonalite is quartz-andesite. The quartz is restricted to the groundmass in such rocks; but as the amount of free silica increases they grade into dacites, which commonly contain first-generation quartz.

In Britain andesites occurring both as lava flows and minor intrusions are found in volcanic fields of several ages. The presumably Precambrian lavas of Jersey are dominantly rhyolites, but are accompanied by more basic lavas which are stated to be andesitic, though there is no doubt that they are basaltic in part: there is no modern description available. Hornblende-andesites of Ordovician age occur in both North and South Wales, Shropshire and the English Lake District. The Welsh andesites are chiefly hornblende and augite-bearing types, while those in Shropshire contain orthopyroxene, now represented by bastite pseudomorphs. The andesites occurring in the Old Red Sandstone of Scotland, where they build the Pentland, Ochil and Sidlaw Hills, as well as the Cheviot Hills in the Border country, are in a much better state of preservation and include types with enstatite, augite and (on Ben Nevis) hornblende. In the British Tertiary volcanic cycle andesitic rocks are but feebly represented, and appear to be always intrusive. Andesites are developed on a much more extensive scale in the mountains of western America, and the existing Japanese and Javanese volcanoes provide ideally fresh andesites in a variety of types (Fig. 108).

(c) THE SYENODIORITES AND TRACHYANDESITES

Although most petrologists are agreed in recognizing the importance of the syenitic and dioritic rocks, opinion is divided in regard to the intermediate category, the syenodiorites and their medium- and fine-grained equivalents. As explained above, we consider that there is a place for this group, in which the two kinds of feldspar,

ANALYSES OF DACITE AND ANDESITES

	I. Dacite, Lassen's Peak, California.	II. Hornblende- andesite, Mount Shasta.	III. Andesite, Blackford Hills, Scotland.	IV. Hornblende- andesite, Glencoe.
SiO ₂	68.72	61.58	57.53	61.49
Al ₂ O ₃	15.15	16.96	16.47	14.98
Fe ₂ O ₃	1.16	1.75	4.42	1.51
FeO	1.76	2.85	3.23	4.05
MgO	1.28	3.67	1.32	3.22
CaO	3.30	6.28	6.16	4.56
Na ₂ O	4.26	3.94	4.13	3.59
K ₂ O	2.78	1.28	2.09	2.80
H ₂ O	0.74	1.30	1.02	1.91
TiO ₂	0.31	0.49	0.91	0.96
Other constituents (chiefly CO ₂) .	0.30	0.25	3.27	1.38
	99.76	100.35	100.55	100.45

I. Dacite, East End of Chaos, Lassen's Peak, California (W. F. Hillebrand).

II. Hornblende-andesite, Mount Shasta, California (H. N. Stokes).

III. Andesite, Blackford Hill, Edinburgh (E. G. Radley).

IV. Hornblende-andesite, Glencoe, Scotland (Anal. E. G. Radley).
"Glencoe and Ben Nevis," *Mem. Geol. Surv.*, 1916, p. 183.

characteristic of the syenites and diorites respectively, are approximately of the same status. The three grain-size groups are:—

Coarse:

Medium:

Fine:

SYENODIORITES
(MONZONITES)

MICROSYENODIORITES
(MICROMONZONITES)

TRACHYANDESITES

THE SYENODIORITES (MONZONITES)

The type-rock was described (as monzonite) by Brögger from the Monzoni Complex in the Tyrol. Admittedly monzonite only makes up a part of the whole Complex, but this applies equally truly to many another valid type. The original monzonite was slightly over-saturated, with 2.5 per cent of free quartz, and therefore by analogy with syenites and diorites should be termed quartz-monzonite. Nearly two-thirds of the rock consists of feldspar, with andesine and orthoclase about equally balanced (32 and 30 per cent respectively). The coloured minerals include augite, biotite and hornblende in order of importance, the colour index amounting to 35.

The most significant fact in the mineral composition of monzonite is the coexistence of orthoclase and plagioclase, normally lying within the oligoclase-andesine range, as in diorites, in approximately equal quantities: neither must amount to less than one-third of the total feldspar. This is the crux of the definition, and is also the justification for using "syenodiorite" as synonymous with, and perhaps preferable to, monzonite. With increasing orthoclase monzonite grades into syenite, with increasing plagioclase into diorite. The amount of coloured silicates in the monzonites so far described is relatively large compared with syenites, and doubtless melamonzonites will be discovered in due course, with colour index above 40; while feldspar-rich types, deficient in coloured minerals, would appropriately be termed leucomonzonites. No restriction need be laid down in regard to the kinds of coloured mineral present. They may be as in the type-rock, or any other combination appropriate to the Intermediate rocks.

In thin section there is usually little difficulty in recognizing the diagnostic feature of the monzonite type: the plagioclase tends to form comparatively smaller crystals of rather better shape than the orthoclase, which is poikilitic towards the plagioclase—a single plate enclosing, it may be, a large number of disorientated plagioclase laths as shown in Fig. 109. The pyroxene, when present, is an almost colourless diopsidic clinopyroxene, which, in many cases, is intimately associated with common green hornblende. The latter is irregularly moulded upon the pyroxene core as a rule, but the two may occur independently. Amphibole of a different kind—a somewhat fibrous "uralite"—tends to replace the pyroxene in altered monzonites.

Olivine-monzonites occur in the Oslo plutonic complex.¹ Oligoclase and alkali-feldspar occur in approximately equal amounts. Although olivine is the most abundant coloured mineral, it is accompanied by biotite and a little pyroxene; the colour index (about 35) is appropriate to an Intermediate, rather than a Basic, rock. The association of olivine with these kinds of feldspar is unusual, and this type of rock does not appear to have been recorded elsewhere.

Monzonites are not widely distributed, judging from existing records, nor do they form large individual intrusions. Like syenites and diorites they form marginal facies of, or offshoots from, larger masses of granitic composition. Thus in this country monzonites occur among the satellitic intrusions associated with the Old Red Sandstone and Caledonian granodioritic complexes. In the great Tertiary ring-complex of Ardnamurchan in western Scotland,

¹ Barth, T., "Studies on the Igneous Rock Complex of the Oslo Region";
ii, *Systematic Petrography of the Plutonic Rocks*, Oslo (1945), p. 57 (under "apetroctolite").

although most of the rocks are basic (eucrites and gabbros), the latest and most central ring dykes consist of quartz-monzonite and tonalite. The view is widely held that most monzonites are hybrids: they have originated by admixture of acid and basic magmas in some deep-seated source. A number of analyses of selected types together with Brögger's average are given in the table on page 274.

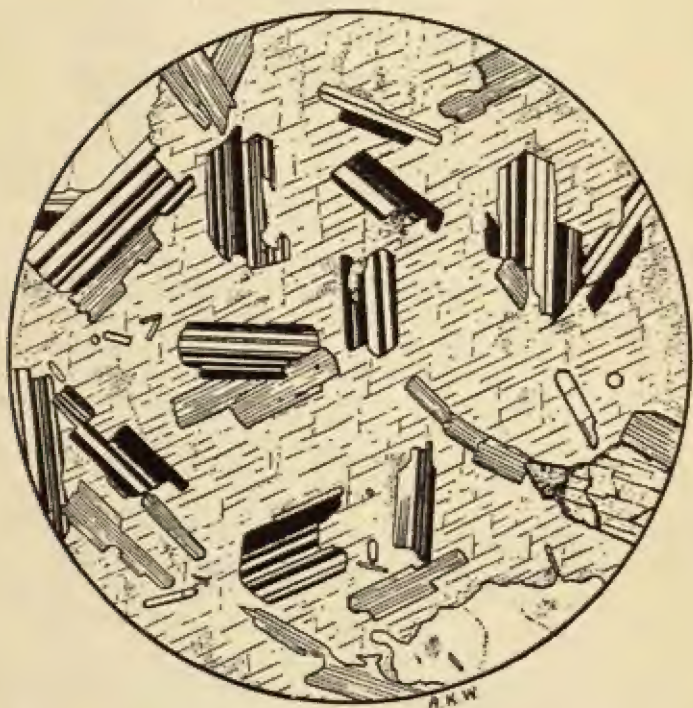


FIG. 109

Quartz-monzonite ("Banatite") above Pechadoire, Auvergne.

Subhedral plagioclase (twinning formalized), diopside augite (right), biotite (ruled), apatite and sphene, all poikilitically enclosed in orthoclase making irregular contact with quartz at edge of section.

MICROMONZONITES (MICROSYENODIORITES)

For the sake of completeness we include as the members of the medium grain-size group equivalent to the monzonites, rocks, which by analogy with the other clans, should be called micromonzonites.

As noted above (p. 234), judged strictly on the basis of their feldspar-content, some Norwegian larvikites are monzonitic, while some rhomb-porphyrines—those of coarser grain—are technically

porphyritic micromonzonites. The finer grained rhomb-porphyrries are trachyandesites.

THE TRACHYANDESITES

The fine-grained equivalents of the monzonites are the trachyandesites (Michel-Lévy, 1894), which bear to trachyte and andesite exactly the same relationship as monzonite (syenodiorite) does to syenite and diorite. The essential fact in their mineral composition which justifies their recognition in the occurrence of alkali-feldspar

ANALYSES OF SELECTED TYPES OF MONZONITES

	I. Quartz- monzonite (Banat Type), Charnwood Forest.	II. Monzonite, Stratherric.	III. Monzonite, Monzoni.	IV. Monzonite, Glen Creran.	V. Monzonite, Brögger's Average.
SiO ₂ . . .	64.30	59.34	54.20	53.22	54.90
Al ₂ O ₃ . . .	17.89	18.91	15.73	17.20	17.44
Fe ₂ O ₃ . . .	4.75	6.22	3.67	2.64	9.64
FeO . . .	—	0.95	5.40	5.09	—
MgO . . .	1.12	2.55	3.40	6.33	3.26
CaO . . .	3.33	3.97	8.50	6.87	6.96
Na ₂ O . . .	3.84	2.61	3.07	2.38	3.50
K ₂ O . . .	3.37	2.91	4.42	4.12	3.51
H ₂ O . . .	1.60	1.43	0.50	0.80	1.23
TiO ₂ . . .	—	0.72	0.40	0.69	0.71
Other con- stituents .	—	0.39	1.21	0.85	—
	100.20	100.00	100.50	100.19	—

- I. Quartz-monzonite, Banat Type, Croft Hill, Charnwood Forest, Leicestershire (E. E. Berry).
- II. Monzonite, Stratherric, Glen Liath, Inverness-shire (W. Mackie), *Trans. Geol. Soc. Edin.*, viii (1905), p. 54.
- III. Monzonite, Monzoni, Tyrol (M. Schmelck).
- IV. Monzonite, Glen Creran, Scotland (Anal. E. G. Radley), "Ben Nevis and Glencoe," *Memoir*, 1916, p. 183.
- V. Brögger's average of fourteen typical monzonites. "Die Triadische Eruptionsfolge bei Predazzo," p. 63.

in notable amounts associated with plagioclase. Normally the plagioclase occurs as phenocrysts while the alkali-feldspar is restricted to the groundmass, where it occurs as a trachytic "felt" of sanidine microlites. In effect it is as if the phenocrysts of andesite had found their way into the groundmass of a trachyte. The mafic minerals are biotite, common augite and common hornblende.

Several specific names have been applied to types of so-called trachyandesites, though not all of these should be included in the family as defined above. One such name is **latite**, from the Italian province of Latia, proposed by Ransome (1898) and adopted by Johanssen as a general name for the family. Washington and others have distinguished several types of trachyandesites in the Italian volcanic province, including **vulsinite**.¹ In the type-rock soda-orthoclase amounts to more than 69 per cent and the plagioclase to only 19. The colour index is 12, while the dark silicates are biotite and the normal pale greenish clinopyroxene so often encountered in the "Intermediate" rocks. Clearly, with so little plagioclase (a good deal less than the requisite one-third of the total), vulsinite is not a trachyandesite as defined above. Further, as the plagioclase is outside the range of composition normal for andesites, it seems best to classify it as a trachybasalt (p. 330). Among the Scottish Carboniferous lavas are some rather basic trachyandesites which have been compared with **banakite**, a type described (with others) from the area of the Yellowstone National Park.² Such rocks border on the trachybasalt, however, as the plagioclase is more basic (labradorite) than that usually found in trachyandesites. The labradorite phenocrysts are rimmed with sanidine, while the ground-mass consists chiefly of microlites of the latter mineral. The coloured mineral is also somewhat unusual for rocks of this family, being aegirine-augite.

The finer grained rhomb-porphyrries of Norway³ are trachyandesites carrying the distinctive phenocrysts of oligoclase or andesine set in a matrix of anorthoclase microlites. Most specimens contain a little accessory quartz.

¹ Johanssen, A., *Descriptive Petrology of the Igneous Rocks*, iv (1938), p. 42.

² "The Geology of East Lothian," *Mem. Geol. Surv., Scotland*, 1910, p. 131.

³ Oftedahl, C., "Igneous Rock Complex of the Oslo Region," Pt. vi, *Skrif. ut. av det Norske Vid. Ak.*, Oslo, 1946, p. 37.

THE BASIC IGNEOUS ROCKS OF CALC-ALKALI TYPE

It is still a matter of great convenience to speak of basic igneous rocks, even though the basis of classification is mineralogical, though basicity is an essentially chemical conception. In the basic rocks we have the direct antithesis of the acid rocks. Three series are included, which vary in alkalinity. The most typical, and those which will be first described on account of their paramount importance, belong to the Calc-alkali Series, the most typical members of which comprise the normal coarse-grained gabbros, the medium grained dolerites and the fine-grained basalts.

I. THE GABBROS AND RELATED TYPES

The means of distinction between diorites and gabbros have been discussed above (p. 257). Typical members of the family under discussion consist of plagioclase within the range labradorite-anorthite, associated with pyroxene, with or without olivine, and it may be with minor amounts of other dark minerals including biotite and rarely hornblende. These essential components may occur in all conceivable proportions. It is essential, therefore, to define a number of central types in terms of these essential components, as tabulated below:

Plagioclase with clinopyroxene	• •	GABBERO
Plagioclase with orthopyroxene	• •	NORITE
Plagioclase with olivine	• • • •	TROCTOLITE •

The presence of any of the other components named above, in significant amounts, is logically covered by using the appropriate type-name, preceded by that of the additional mineral. Thus, many gabbros and norites, fundamentally as defined above, contain some olivine, and must therefore be distinguished as **olivine-gabbro** and **olivine-norite** respectively.

Similarly many norites contain some clinopyroxene, just as many gabbros contain some orthopyroxene: in fact there is a perfectly continuous gradation in the proportion of clino- to orthopyroxene—in combination with plagioclase, of course. Some of these rocks are fundamentally gabbros, and others are fundamentally norites. It

seems to us obvious that there is only one point at which the line between the two should be drawn: at the point where augite equals hypersthene. If the former is in slight excess the rock is hypersthene-gabbro: if the proportions are reversed, it is augite-norite.

As regards **texture**, these rocks are commonly hypidiomorphic granular, the essential minerals occurring as anhedral grains. In many rock-masses the grain tends to vary rapidly from point to point. In certain areas the grain may be notably coarse, and the term pegmatitic is appropriate to such facies.

TABLE SHOWING THE RELATIONSHIP BETWEEN CERTAIN
BASIC ROCKS AND THEIR ULTRAMAFIC DERIVATIVES

Orthopyroxene	100	50	0
Clinopyroxene	0	50	100

COLOUR INDEX	HYPERSTHENITE			DIALLAGITE	
	ORTHONORITE	NORITE	AUGITE-NORITE	HYPERSTHENE-GABBRO	ORTHO GABBRO
90					
10					
	LEUCONORITE			LEUCOGABBRO	
0	ANORTHOSITES				

Less commonly the texture may be ophitic (Fig. 110), though this is more often developed in the medium-grained microgabbros (dolerites).

Orbicular norites and gabbros have been described from several localities including Romsaas in South Norway, the Kenora District in Ontario, San Diego County, California¹ and Corsica. Under the name "corsite" (Zirkel) or "napoleonite" the rock from the last-named locality is probably the best-known of all orbicular rocks, though it is often referred to as orbicular diorite, on the grounds that it consists of amphibole and plagioclase. Actually it is thoroughly

¹ Schaller, W. T., "Mineralogical Notes," Series 1, *Bull. U.S. Geol. Surv.* No. 490 (1911), p. 58.

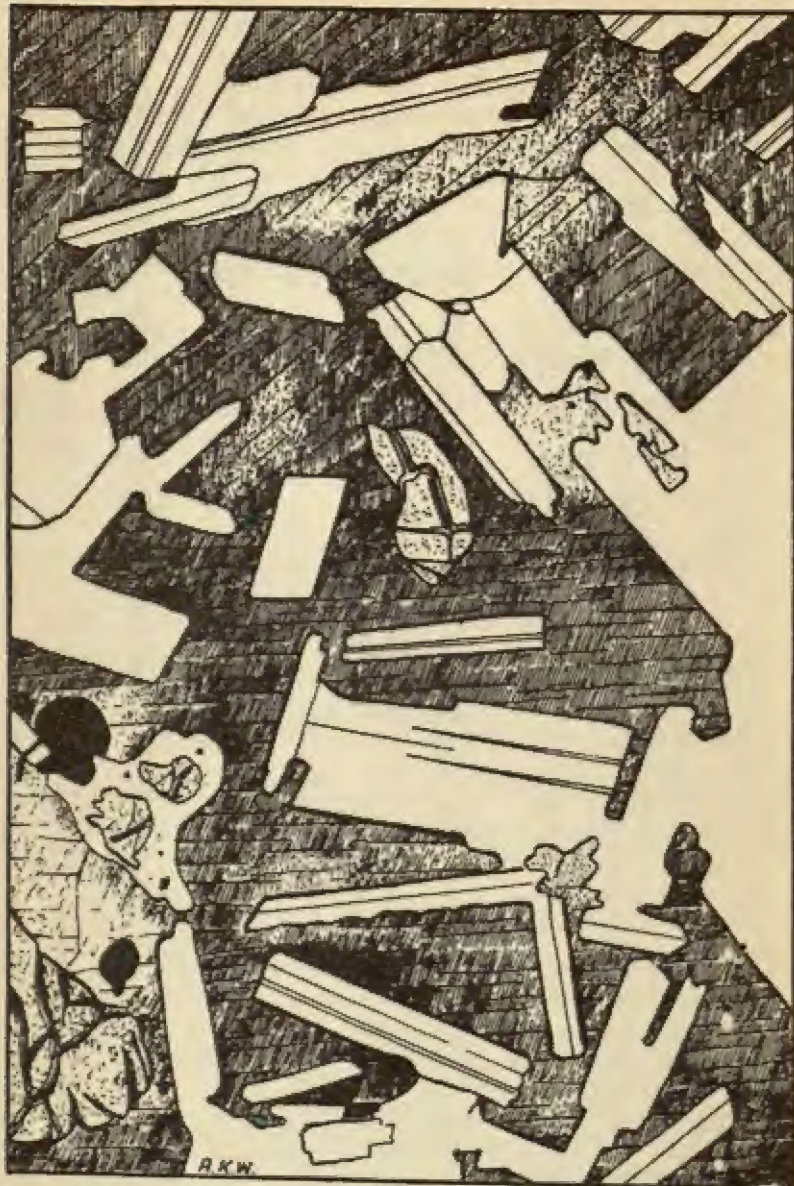


FIG. 110

Olivine-gabbro with ophitic texture.

Three small olivines partly altered to serpentine embedded in strongly schillerized clinopyroxene in ophitic relationship to labradorite. Iron-ore rare, in rounded patches and minute octahedra in the serpentine. (Size of section 6 mm. \times 9 mm.)

basic,¹ with 46 per cent of silica; the plagioclase is bytownite (An_{73}), while the amphibole is, in part, paramorphic after pyroxene. Approximately three-quarters of the rock consists of bytownite and one-quarter of amphibole. The orbs average an inch in diameter, though they may reach three inches, and a central section shows a core of normal texture, surrounded by alternate shells of plagioclase and amphibole. The matrix is of normal texture.

Gabbro.—Many gabbros are of almost ideal composition, consisting in thin section of large irregular grains of the two components, labradorite and clinopyroxene. The former is commonly twinned on the Albite, Carlsbad and Pericline laws. Zoning is not common; but the mineral is often schillerized, with multitudes of regularly orientated minute opaque rods (Fig. 113) or plates. In some cases the rods are almost submicroscopic, when they impart a cloudiness to the crystals. Under certain conditions, considered below, the plagioclase breaks down to an aggregate of grains of zoisite, or some other member of the epidote group, embedded in albite.

The pyroxene is normally a common augite, but it often shows the additional parting parallel to (100) characteristic of diallage. Not infrequently the clinopyroxene shows numbers of sheet-inclusions of orthopyroxene, identified, when they are of sufficient width, by their weaker birefringence and straight extinction in some sections. There may be several sets of these regularly arranged sheet-inclusions that clearly resulted from exsolution with falling temperature.

Olivine, when present, shows its normal characters. On account of the high temperature at which it separates from the magma, it is the first essential mineral to crystallize, and therefore tends to show a better shape than the pyroxene and plagioclase in which it is embedded. Naturally it may show any degree of alteration to one of the serpentine minerals.

Varieties.

Orthogabbro (*i.e.*, gabbro agreeing closely with the definition of the ideal type), contains neither quartz nor olivine; but olivine-gabbro is common, while **quartz-gabbro** is not unduly rare. The quartz is usually intergrown with orthoclase, also present in small quantity, forming a type of micropegmatite in interstitial patches. This feature is much commoner in the medium grained dolerites.

In **olivine-gabbros** the reaction relationship between the various coloured components is often particularly well displayed. Olivine is rimmed with pyroxene, while amphibole envelops the latter, and is in turn surrounded by biotite (Fig. 111). The order of

¹ Tröger, E., "Quantitative Daten einiger magmatische Gesteine," *Zsch. M.P.M.*, xlv (1934), p. 167.

the successive rims is that of the minerals comprising Bowen's discontinuous reaction series. Rims of a quite different nature provide one of the most fascinating textural characters of the igneous rocks. They have been variously spoken of as "reaction rims," or "coronas," and take the form of narrow mantles often of singularly uniform width, sometimes single, but in other cases double, round olivine crystals embedded in plagioclase. These textures therefore tend to be more uniformly developed in rocks



FIG. 111

Olivine-gabbro, Wolf Cave, Jersey.

Olivine, titanite, barkevikite and plagioclase.

(Reproduced by courtesy of the Council of the Geologists' Association.)

of troctolitic type, and are more fully described under that heading.

A certain amount of iron ore is present in all normal gabbros. It may be magnetite, but is more often either titaniferous magnetite or ilmenite. The basal portions of some gabbro masses become enriched in iron-ore, which may make up a considerable part of the whole rock. On the other hand Wager and Deer¹ have applied the name **ferrogabbro** to some rocks occurring in the Skaergaard intrusion in Greenland, which contain both pyroxenes and olivines

¹ "Geological Investigations in East Greenland, Part iii. The Petrology of the Skaergaard Intrusion . . . East Greenland," *Meddelelser om Grønland*, Bd. 105, Nr. 4 (1939), p. 98.

abnormally rich in *combined* iron: the clinopyroxene in some examples contains ferrosilite up to 74 per cent, and the "olivine" is nearly pure fayalite.

Norite.—In Orthonorite all but an insignificant proportion of the pyroxene is hypersthene or bronzite. In augite- (or diallage-) norite, clinopyroxene occurs in significant amounts, but must not exceed half the total pyroxene-content, or the rock is termed hypersthene-gabbro.¹ A very distinctive feature of these orthopyroxenes is schiller structure resulting from regularly arranged brownish pleochroic plates, of uncertain composition. Further, they are often heterogeneous by reason of the regular inclusion of exceedingly narrow sheets of clinopyroxene, easily identified by their stronger birefringence and widely oblique extinction. There may be up to four sets of these plates, lying parallel, according to Wager and Deer, to the faces of the "general form" (111).² In addition there may be a lamination parallel to (100) simulating a very fine lamellar twinning, but the two individuals are not related according to a constant law.³ Both sets of lamellae have the same optical characters, but different orientation, so that they are separated by a difference in extinction angle of between 10 and 15 degrees. This structure is only visible between crossed polarizers, near the extinction position, in suitably orientated sections.

A characteristic feature of certain noritic rocks is the development of **symplectic intergrowths** along intercrystal boundaries. They consist of a myrmekite-like bulbous outgrowth of plagioclase, occasionally, though rarely, twinned in a normal manner, riddled with vermicular inclusions of orthopyroxene. In the example illustrated in Fig. 112 the vermicules have grown away from vein-like masses of titaniferous magnetite rimmed against labradorite with grains of fayalitic olivine, and associated at one point with poikilitic biotite. The olivine itself is locally intergrown with vermicular magnetite. There is no doubt that this phenomenon dates from a late stage in the crystallization of the magma. Similar intergrowths of the same two minerals may frequently be seen in the well-known European norite from Hitteroe, Norway (Fig. 113). In Britain norites occur in association with other basic rocks in sheet-like intrusions (or perhaps one single sheet) covering a large area in Aberdeen and Banff, Scotland; but they are developed on the grandest scale in the Bushveld Complex in the Transvaal. Although this, the greatest individual basic intrusion in the world,

¹ It must be noted that in important papers and Survey Memoirs H. H. Read restricts the term norite to rocks with hypersthene exclusively.

² *Meddelelser om Grønland*, Bd. 105, Nr. 4 (1939), p. 97.

³ Henry, N. F. M., "Lamellar Structure in Orthopyroxenes," *Min. Mag.*, 1942, p. 179.



FIG. 112

Reaction Phenomena and Symplectic Structure in Magnetite-Anorthosite, Magnet Heights, Sekukuniland, South Africa.

In this rock titanomagnetite runs between the plagioclase crystals, while a distinctive feature is the reaction rim of fayalitic olivine which insulates the iron-ore from the feldspar. Myrmekite-like symplectites of orthopyroxene and plagioclase are lobed into the labradorite. Mg-rich mica is intimately associated with the olivine at one point, while the latter contains dendritic magnetite.

Orthopyroxene, light stipple; fayalitic olivine, close stipple; mica, lined; iron-ore, opaque. Twinning indicated in the plagioclase.

is commonly spoken of as the "Bushveld Norite," it is not wholly made of this one type, but exhibits an extraordinary range of noritic, gabbroic and ultrabasic types. The noritic range varies from rocks which are nearly pure plagioclase, with very minor amounts of bronzite and accessories, through normal types to others just as melanocratic, grading with the diminution of feldspar into ultrabasic pyroxenites (bronzitites). The highly feldspathic types are *leuconorites*, sometimes called noritic anorthosites (see below).

Origin and relations.

In analyses of normal gabbros and norites, alumina (Al_2O_3) is restricted to plagioclase and clinopyroxene, and perhaps the most



FIG. 113

"Norite," Hitteroe, Norway.

A large apatite is in contact with light green clinopyroxene associated with iron-ore. The pyroxene is fringed with a myrmekite-like intergrowth of the same pyroxene and plagioclase, lobed into schillerized labradorite. The latter contains regularly orientated short rods of iron-ore, and also colourless tubular inclusions whose orientation is controlled by the twinning. (*Bottom, right.*)

important condition for the formation of orthopyroxene is that the magma should not contain more alumina than can be accommodated in the plagioclase. Obviously, too, there must be adequate MgO and sufficient silica to ensure that ultimately the metasilicate $(\text{Mg,Fe})_2\text{Si}_2\text{O}_6$ shall be formed, and not the orthosilicate $(\text{Mg,Fe})_2\text{SiO}_4$.

	Olivine norite	Olivine gabbro	Olivine-free norite	Olivine-free gabbro
SiO_2	47.34	46.49	51.38	49.25
Al_2O_3	15.64	17.73	17.19	17.49
$\text{FeO} + \text{Fe}_2\text{O}_3$	9.17	9.83	10.25	9.72
MgO	13.95	8.86	7.17	6.61
CaO	8.73	11.48	8.37	10.61

The analyses quoted above show the significant components only in olivine-norite (average of 10), olivine gabbro (average of 17), olivine-free norite (average of 60), and olivine-free gabbro (average of 184). Both norites and olivine-norites are slightly more siliceous, slightly richer in iron and magnesia, but notably poorer in lime than the corresponding types of gabbro.¹ From these figures it may be deduced that (1) with a sufficient amount of CaO available clinopyroxene of the diopside-hedenbergite range will form; but (2) with insufficient CaO clinopyroxene is ruled out and orthopyroxene of the enstatite-ferrosilite range will be formed instead, other things being equal.

We may refer at this point to the contaminated norites of Haddo House, Inch and Arnage (see map, Fig. 139).² In addition to the hypersthene and plagioclase proper to a norite, these rocks contain a red-brown biotite, crowds of dark green spinels and numbers of particularly striking cordierite crystals, like those illustrated in Fig. 60. These minerals, normally found in metamorphic rocks, doubtless represent local excesses of aluminous material derived by incorporation of silica-poor, richly aluminous xenoliths, some of which have survived in the norite. The country-rock from which these xenoliths were derived is actually andalusite-cordierite hornfels rather richer in silica, but poorer in alumina, than the xenoliths. It is inferred, therefore, that on incorporation in the gabbroic magma, the xenoliths contributed silica and alkalis to the magma, and received from the latter a proportional increase in Al⁺⁺⁺.

The survival of richly aluminous inclusions can be only a temporary phase in the assimilation process, however; with more complete digestion, and more even distribution of the products of assimilation, the cordierite and spinel in turn disappear. H. H. Read, who has made a special study of the process, points out that the incorporation of the aluminous material causes early precipitation of anorthite (in the plagioclase), which so depletes the magma of calcium that there is none available for the formation of the diopside molecule (in clinopyroxene) and therefore hypersthene forms in its stead. Read concludes from this that this process may well be the ultimate cause of the production of noritic magma, and has stated that, "if there were not so many slates there would not be so many norites." At the same time it is well to remember that orthopyroxene is a normal member of Bowen's discontinuous reaction series, and

¹ Johanssen, A., *Descriptive Petrology of the Igneous Rocks*, iii (1937), Tables 78 and 80.

² "The Gabbros and Associated Xenolithic Complexes of the Haddo House District, Aberdeenshire," *Quar. Journ. Geol. Soc.*, xci (1935), p. 591, with further references on p. 634 of this paper.

may be expected to crystallize normally from a magma of the appropriate composition.

The rocks termed **eucrite** in publications by the Officers of the Geological Survey are of "mixed" composition, in the sense that they carry hypersthene up to half the total pyroxene present, associated with clinopyroxene and olivine, together with anorthite. In accordance with the definitions given above, eucrite is an olivine-hypersthene gabbro, with a plagioclase more calcic than usual. Whether or not the nature of the plagioclase is sufficient justification for using a new type-name is a moot point: but there is certainly less to be said for expanding the term, as has been done recently, so as to include similar assemblages of dark minerals, but with bytownite or even basic labradorite as the feldspar. These eucrites in any case are important rocks in some of the Tertiary ring-complexes in Scotland, the Great Eucrite of Ardnamurchan being a typical example.

Troctolite.—The third of our main types consists of the combination olivine-plagioclase, with minor amounts of accessory minerals. A typical specimen of troctolite, especially if somewhat weathered, is a striking-looking rock, the grey plagioclase-aggregate being studded with black, brown or reddish olivines or pseudomorphs after olivine. This accounts for the popular name, "troutstone," often applied to this rock. In thin section the olivines are seen to be insulated from the plagioclase by reaction rims of orthopyroxene, usually very thin, but in special types they may be thicker and double. If the olivine has been serpentinized, the expansion resulting from the change in composition causes intense shattering of the surrounding plagioclase. The fractures radiate out from the olivine nuclei, often in a manner simulating dyke swarms (Fig. 114).

The finest display of troctolites in Britain is found in the basic complex at Belhelvie in Aberdeenshire.¹ This is a layered concordant intrusion, partly ultrabasic, though mainly consisting of troctolite grading into norite, hypersthene gabbro, and even, if one considers a small enough specimen, anorthosite and dunite (p. 342). In the troctolites proper the proportion of labradorite (An_{70}) to olivine (For_{70}) varies considerably. In an average specimen, the analysis of which is given under No. 1 on p. 295, the mineral composition is bytownite 70.5, olivine 28.4, and pyroxene 0.6 per cent.

Texturally the Belhelvie troctolites are interesting on several counts. The olivines are uniformly rimmed with reaction products, the inner zone consisting of orthopyroxene or amphibole in different cases—both colourless varieties—while the outer zone is a horn-

¹ Stewart, F. H., "The Gabbroic Complex of Belhelvie, Aberdeenshire," *Quar. Journ. Geol. Soc.*, cii (1947), p. 465.

blende-spinel symplectite. Corona structure of this type is illustrated in Fig 115, and is believed to be due to the action of liquid residua at high temperatures.¹ Secondly, the degree of idiomorphism exhibited by the two chief minerals depends upon their relative proportions: with olivine in excess of a certain amount, this mineral separates before the plagioclase, and is therefore euhedral towards

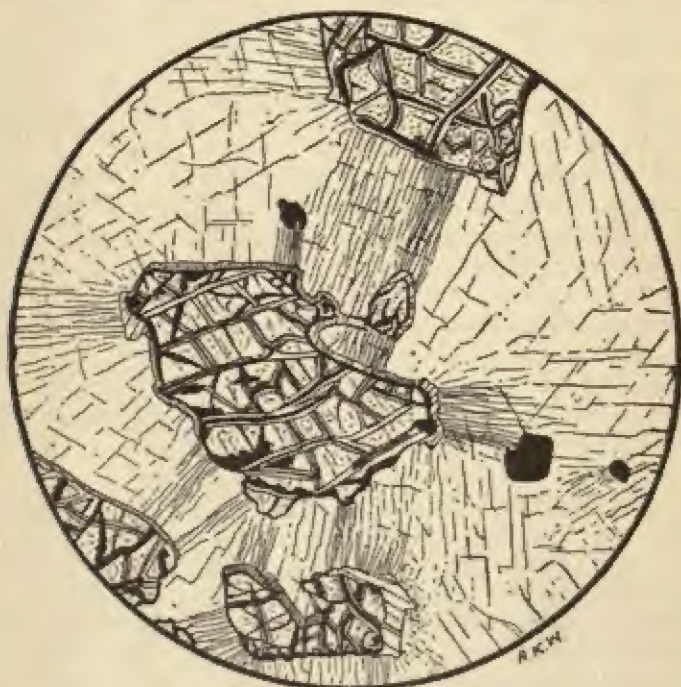


FIG. 114

Troctolite, Belhelvie, Aberdeen, Scotland. Olivines, veined by serpentine with separation of magnetite, in plagioclase traversed by systems of closely spaced fractures. Occasional primary magnetite crystals. A thin veneer of orthopyroxene surrounds the olivines which measure 2-3 mm.

it. With plagioclase in excess, the olivine crystallizes late, and is interstitial towards the earlier, and therefore better formed, plagioclase. When present in eutectic proportions both crystallize together, neither has the advantage over the other, and neither therefore is euhedral. Finally, in places the troctolites develop a pegmatitic facies, with crystals of olivine up to 2 cm. in diameter.

Harker, when describing the ultrabasic-basic complex of the

¹ Cf. Shand, S. J., "On Coronas and Coronites," *Bull. Geol. Soc. Amer.*, lvi (1945), p. 247.

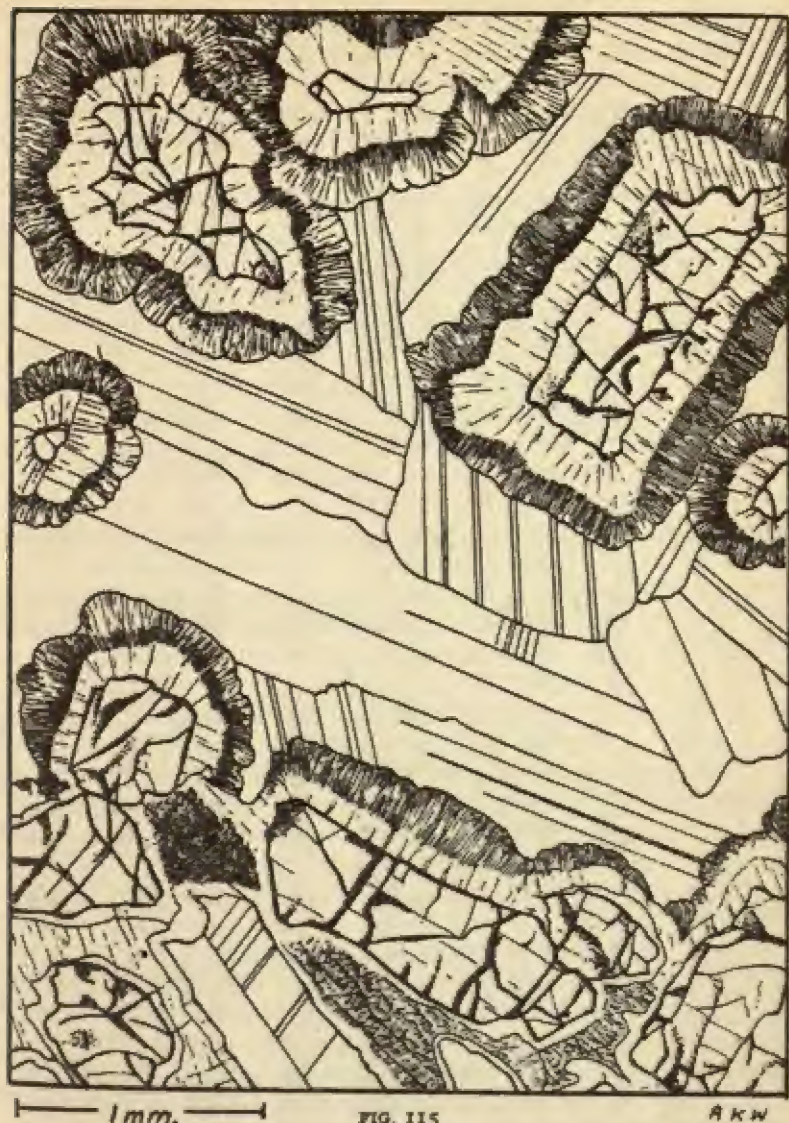


FIG. 115

AKW

Augite-cummingtonite-olivine-norite, Risør, Norway.

Corona structure is finely developed around cores of olivine. The coronas consist of orthopyroxene with a sharp boundary against an amphibole which in places is cummingtonite, but elsewhere the place of the latter is taken by a very light green symplectite, crowded with irregular vermicules. Cummingtonite occurs in association with bright green spinel around iron-ore, while the former occurs as a very thin but regular zone around schillerized clinopyroxene. (Lower part of the drawing.)

Island of Rum, Scotland, coined the name **allivalite** from the peak of Allival, for a rock which is essentially a troctolite, but with anorthite instead of labradorite. Actually among the Belhelvie troctolites are some with labradorite, others with bytownite, while some contain anorthite and are therefore identical with Harker's allivalites.

As a matter of convenience we include with the gabbroic and noritic rocks the **anorthosites**, which are essentially monomineralic, being almost pure basic plagioclase rocks. They are sometimes grey on account of the schillerization of the plagioclase, but may be white. Any of the coloured or accessory minerals of the norite, gabbro, troctolite range may be associated with the plagioclase, and there is a perfect gradation into one or other of these types with increasing amounts of dark minerals. Bodies of anorthosite range in size from layers a few inches thick, occurring as integral parts of ordinary basic igneous rocks such as gabbros and norites, to vast masses occurring in the Precambrian Shield areas, such as the Morin and Saguenay anorthosites. The latter is estimated to cover an area of 5800 square miles, and is of unknown thickness. Finally, we may note such occurrences as the anorthosite sheets in the Bushveld and Sierra Leone noritic complexes. Excluding for a moment the great Precambrian Shield anorthosites, it is obvious that the anorthosite sheets, whether they be 3 inches thick as at Belhelvie, or many yards as in the Bushveld Complex, represent a *part*, that is, a differentiate, of a normal gabbroic or noritic magma. Much has been written concerning the origin of the anorthosites. The nature of the problem is simply stated: by what process have the plagioclase crystals represented by the anorthosite layers been separated from the olivine and pyroxene crystals, represented by the complementary, ultrabasic layers, made up almost completely of these minerals? Surely the answer must be, "gravity." Given that there is a slight specific gravity difference between the coloured minerals and the magma, the former must sink. If the plagioclase is lighter than the magma, these crystals must tend to rise: even if they have the same specific gravity as the magma, they will tend to form a self-supporting crystal-mush from which the residual liquid might be squeezed out by so-called filter-press action. If the pressure exerted was considerable, the plagioclase crystals might be somewhat crushed, to the extent of showing peripheral granulation. It is significant that these effects can sometimes be discerned under the microscope. Even in hand-specimens anorthosites from some occurrences appear porphyritic, but the texture is really *pseudo-porphyrritic* and arises from the peripheral granulation of plagioclase crystals of particularly large size, the matrix really consisting

of an aggregate of fine grains ground off the edges and corners of the "phenocrysts." These effects of cataclasis are often seen in specimens from the great Precambrian anorthosites, the genesis of which is not so obvious, for, even if they are accumulations of plagioclase crystals produced in the manner outlined above, it still remains to explain how such a crystal-mush came to be separated from the complementary rock-types with which it should be associated if the mechanism was the same. There is only one possibility: movement of the crystal-mush would be possible only if there were sufficient liquid remaining entrapped between the crystals to lubricate the mass. There can be no doubt that pressure sufficient to move the crystal-mush from its point of origin to the place where it now occurs, might produce some granulation of the plagioclases, and would almost certainly squeeze out the interstitial liquid in the ultimate phase, leaving a more or less pure concentrate of plagioclase crystals.¹

Banding.

The most striking and also one of the most puzzling features of "gabbroic" complexes is the banding so well displayed in many exposures. Nearly every gabbroic mass of any size shows banding to some degree, the most spectacular examples being found in the giant lopolithic intrusions such as the Bushveld in South Africa, and the Duluth, Sudbury and Stillwater complexes in North America. Although on a much smaller scale, good examples are afforded by the well-known banded gabbros in Skye, and the extraordinary sheeted complex in the island of Rum. In most of these occurrences, the dominant rock-types are noritic.

Although the banding is sufficiently variable in character as to suggest more than one cause, certain features are common to most types of banding. Thus the layers normally have dip and strike parallel to the margins of the intrusion, while the phenomenon is best displayed in the marginal parts of the latter. Apart from these features, however, the banding varies widely in scale and extent, and in the mineral contrasts between contiguous layers. The individual bands vary in width from a fraction of an inch to many yards; they may fade out in a matter of a few yards, or they may maintain their characters unchanged over a distance of many miles. Normally the regularity of the banding is very striking: and although the bands are occasionally contorted due to plastic flow, they seldom, if

¹ Bowen, N. L., "The Problem of the Anorthosites," *Journ. Geol.*, xxv (1917), p. 209, but compare Miller, W. J., "Adirondack Anorthosite," *Bull. Geol. Soc. Amer.*, xxix (1918), pp. 410, 426 and 456; also *Journ. Geol.*, xxxix (1931), p. 337.

ever, show transgressive tendencies. The layering results from systematic variations in the proportions of the ordinary gabbroic or noritic minerals, plagioclase, pyroxene and olivine. Occasionally a remarkable concentration of ore-minerals may give rise to bands consisting almost exclusively of titaniferous magnetite, ilmenite or chromite, as in the "critical zone" of the Bushveld Complex. The texture of different layers remains fairly constant, chilled margins are absent, and crystals near the margins of one band interlock with those in adjacent ones, although, in many instances, the junctions may be singularly sharp (Fig. 116).

The most pronounced layering in Rum¹ is exhibited by the ultrabasic-basic complex which builds the twin hills of Allival and Askival. The complex comprises a large number of sheets, individually up to 150 feet in thickness, alternately peridotite and allivalite. Harker originally thought the banding to be due to successive injections of two contrasted magmas, following one another in quick succession, so that no appreciable chilling of one band against another took place. After making a special study of the contact zones between the successive sheets, S. I. Tomkeieff² has concluded that the field relations could have been produced only by the streaking out of a heterogenous magma, consisting of two contrasted fractions, but intruded all at once.

Probably the type of banding which is most easily understood is that to which the name "gravitational mineral banding" may be applied. This involves a gradation from top to bottom of a sheet, the lighter, feldspathic components being concentrated towards the top, and the ferromagnesian components towards the base. Clearly the only force that it is necessary to invoke in such cases is gravity, and the essential condition is a difference in specific gravity between the crystals and the magma in which they were suspended. If the crystals are heavier they will tend to sink, if lighter, to float upwards, and in either case the crystals must displace their own volume of liquid. The result is **gravitational layering**. The process is easy to visualize, and there is no doubt that differential sinking of crystals in a liquid environment is the fundamental cause of layering of this kind. But gravitational sorting alone does not satisfactorily account for **rhythmic layering**; neither does it explain the clear-cut contacts between contiguous bands. Rhythmic layering is probably nowhere better displayed than in the magnificent occurrences described by Wager and Deer from Eastern

¹ "Geology of the Small Isles of Inverness," *Mem. Geol. Surv.*, 1908, p. 74.

² "On the Petrology of the Ultrabasic and Basic Plutonic Rocks of the Island of Rum," *Min. Mag.* xxvii (1945), p. 127.



FIG. 116

Contact-zone between hypersthene-anorthosite and chromitite,

Dwars River, Bushveld Complex, Transvaal, South Africa.

The outlines and nature of the twinning in the plagioclase are indicated. Hypersthene stippled; chromite in single crystals and groups of octahedra increasing in size and concentration downwards.

Greenland.¹ As illustrated in Fig. 117, the gabbroic rocks in the Skaergaard Complex in places exhibit typical gravitational layering in thin bands, separated by thicker layers of "average rock" showing no crystal sorting. Thus the factors operating to produce the crystal sorting only became effective at intervals during cooling of the magma. Several suggestions as to the causes of such rhythmic layering have been made. Periodic agitation of the magma during crystallization would certainly aid crystal sorting by dislodging



M.K.W.

FIG. 117

Gravity differentiated layers separated by layers of average rock in the Skaergaard complex, in Eastern Greenland.

(After Wager and Deer, *op. cit.*, plate 8.)

the heavy crystals temporarily held up in the crystal mesh, and by tending to keep the lighter plagioclases suspended. Freedom from such agitation would tend to give a layer of normal unbanded rocks.

In the Skaergaard banded rocks the plagioclases, of platy crystal habit, lie with their flat faces in parallelism, and thus impart a

¹ Wager, L. R. and Deer, W. A., "Geological Investigations in Eastern Greenland, Part iii, The Petrology of the Skaergaard Intrusion," *Meddelelser om Grønland*, Bd. 105, Nr. 4, 1939, pp. 36 and 271.

Coats, R., "Primary Banding in Basic Plutonic Rocks," *Journ. Geol.*, xlv (1936), p. 407.

Hess, H. H., "Primary Banding in Norite and Gabbro, *Trans. Amer. Geophys. Union*, 19th Ann. Meeting, 1938.

well-developed **igneous lamination** to the rocks. Further, crystals of prismatic habit, pyroxenes for example, may show a parallel lineation, and it is evident that movement due to convection currents within the magma has played an important part in producing the layering. Changes in the velocities of the currents during gravitational sorting have been urged as the cause of the sharp contacts between consecutive layers. It appears to be definitely established that, although crystallization would commence in the upper parts of an intrusion, the crystals would accumulate, under the influence of gravity on its floor, under conditions closely akin to sedimentation, and a large part of the phenomena of layering may be due to winnowing by currents. Certainly gravitational layering is analogous, in a sense, to graded bedding in a sediment.

Late-Stage Alteration of Gabbroic Rocks.

Gabbroic rocks are subject to alteration which may result in the complete replacement of all the original components. Olivine is the first to show these effects: not uncommonly in olivine-gabbros in which the plagioclase is ideally fresh, all the olivine has been changed into serpentine, with the usual separation of magnetite. Hypersthene and bronzite seem to alter more readily than augite—usually into bastite. Clinopyroxene is more variable in its behaviour, but usually goes direct into acicular actinolite of the uralite variety, associated with a peppering of magnetite. With more advanced alteration the actinolite in turn gives place to a more massive green hornblende. In other cases clinopyroxene is changed into chlorite, often penninite, containing rosettes or grains of epidote. Plagioclase too is unstable under the new conditions, and is converted into albite charged with often finely divided lime-rich silicates such as zoisite or some other member of the epidote group, which may be associated with calcite. This aggregate may render the feldspar semi-opaque, and the individual minerals in it may be very difficult to identify, though in other cases there is no doubt as to their identity. More advanced alteration may convert the albite into white mica, and the plagioclases can then be identified only by their shape, not by their substance, for they contain only epidote or zoisite and white mica. Ilmenite may disappear entirely, and be represented by patches of magnetite grains, associated with sphene; but less drastic alteration leaves it with its original shape, but with the characters of leucoxene.

In general these changes are characteristic, in varying degree, of the older gabbroic rocks: in this country the Ordovician basic intrusives in Merionethshire, and the minor intrusives of the Harlech Dome furnish typical examples, and there is little doubt that the

effects are due to mild dynamo-metamorphism. But some of the changes noted are shown by Tertiary gabbros, for example, in localities where they have not been subjected to metamorphism, and the alteration is regarded as an end-stage (or late-stage) phenomenon due to concentration of volatiles. Actually it is not necessary to invoke any agent more drastic than water, which appears to be solely responsible for the conversion of olivine into serpentine, hypersthene into cummingtonite, augite into actinolite or chlorite. In this connection it is significant that rocks in the upper parts of layered intrusive complexes are usually altered most; while those types produced late in an intrusive sequence, and which on general grounds might be expected to have been closely associated with residual liquids, are likewise most affected.¹ This is true, for example, of the quartz-gabbros of the Tertiary ring-complexes in Scotland.

Analyses of typical gabbroic rocks are included in the table on page 295.

II. THE MICROGABBROS

The representatives of the gabbroic rocks, considered above, which fall within the limits of the medium grain-size group should logically be termed microgabbros, as they are exactly comparable with microgranite, microsyenite and microdiorite. Unfortunately the logic of this was not realized sufficiently early, and two other names are in vogue at the present time. In Britain many petrologists use the name **dolerite** instead of microgabbro, though with different shades of meaning. To some the name implies *all* medium grained rocks of gabbroic composition, regardless of age, texture and mode of occurrence. Others restrict it to rocks of the appropriate composition exhibiting ophitic texture only; while yet others use it to cover such rocks provided they are of a hypabyssal mode of occurrence. In our view, if "dolerite" is to be used instead of "microgabbro," the name should cover *all* rocks of the appropriate composition irrespective of textural features, which can in any case be adequately covered by qualifiers. In America "diabase" replaces "dolerite"; but in this country, in spite of a veto by the Committee on Petrographic Nomenclature, some petrologists use the term in much the same sense as Rosenbusch did, for pre-Tertiary dolerites. That is, a **diabase** in this country is a rock of doleritic composition, which is altered to such an extent that few, if any, of the original minerals have survived. In view of these inconsistencies, there is a strong case for the general adoption of "microgabbro."

So far as mineral contents are concerned microgabbros closely resemble gabbros, norites, etc., and there is consequently no need to

¹ Stewart, F. H., op. cit. supra.

ANALYSES OF GABBROS, NORITES, ETC.

	I. Troctolite, Belhelvie.	II. Olivine-gabbro, Sligachan.	III. Norite, Huntly.	IV. Olivine-Norite, Haddo House.	V Norite, Bushveld Complex.	VI. Allivalite, Rum.
SiO ₂	40.21	45.39	49.18	46.98	52.05	42.20
Al ₂ O ₃	24.22	26.34	16.00	18.00	17.24	17.56
Fe ₂ O ₃	0.54	2.02	0.02	1.11	0.65	1.20
FeO	4.48	3.15	8.22	6.93	6.65	6.33
MgO	9.30	4.82	9.47	12.56	8.98	20.38
CaO	11.41	15.29	12.54	10.23	11.37	9.61
Na ₂ O	1.92	1.63	2.04	1.92	1.83	1.11
K ₂ O	0.16	0.20	0.26	0.65	0.40	0.11
H ₂ O	6.86	0.58	0.48	0.79	0.21	1.19
TiO ₂	0.10	0.26	1.24	0.62	0.63	0.09
Other constituents .	1.03	0.14	0.85	0.44	0.25	0.45
	100.23	100.82	100.30	100.23	100.26	100.23

I. Troctolite, W.N.W. of Hillhead of Craigie, Belhelvie, Aberdeenshire (Anal. F. Stewart), *Q.J.G.S.*, cii (1947), p. 474.

II. Olivine-gabbro, Cuillin laccolith, west bank of Sligachan River, Skye. W. Pollard, "Summary of Progress" *Geol. Surv.*, 1899, p. 173.

III. Norite, Huntly, Aberdeenshire. (Anal. E. G. Radley.) Huntly, *Mem. Geol. Surv.*, 1923, p. 115.

IV. Olivine-norite ("Olivine-gabbro," Read). (Anal. S. Parker.) *Q.J.G.S.*, xci (1935), p. 627.

V. Average of five analyses of Bushveld norite, Transvaal. A. L. Hall, "The Bushveld Igneous Complex," *Mem. Geol. Surv., S. Africa*, 1932.

VI. Allivalite, 70 yards south of summit of Allival, Rum. W. Pollard, "Summary of Progress," *Geol. Surv.*, 1903, p. 56.

describe them in detail. The central type consists of plagioclase, near to labradorite in composition, clinopyroxene (usually common augite, though titanite often takes its place), and iron-ore, which in different specimens may be magnetite, titanomagnetite, or ilmenite. The addition of olivine gives olivine-microgabbro (olivine-dolerite); while the incoming of quartz gives quartz-microgabbro (quartz-dolerite). The latter rocks are, of course, oversaturated, and in them orthopyroxene may replace, wholly or in part, the augite of the typical microgabbro (dolerite). There is just as much justification for giving such rocks a distinctive name, as there is for differentiating between gabbro and norite: they are, indeed, **micronorites**, olivine-micronorites or quartz-micronorites according to their degree of silica-saturation. The two pyroxenes may be present in all proportions, and as for the coarse-grained equivalents, the division is most conveniently drawn, quite arbitrarily, at 50 per cent. If therefore orthopyroxene is dominant, the rock is micronorite; but if clinopyroxene predominates, it is microgabbro. The qualifiers "mela-" and "leuco-" are used to signify respectively richness or deficiency in coloured minerals.

The occurrence of two or more pyroxenes in these rocks is a common feature. The clinopyroxene is frequently strongly schillerized parallel to (001) and when the crystal is in addition twinned on (100) it exhibits a distinctive herring-bone structure. The orthopyroxene is commonly hypersthene, appreciably though faintly pleochroic in some sections, devoid of twinning unless it has inverted from pigeonite, and as a rule easily distinguished by its optical characters. Some crystals contain irregular cores of normal hypersthene which are surrounded by an irregular mantle of "hypersthene-perthite." This consists of hypersthene riddled with plates or irregular vermicules of clinopyroxene thrown out as a consequence of exsolution. All three types of pyroxene may be studied in sections of the Palisades sill, New York, which may be described as a quartz-hypersthene-microgabbro. The quartz in rocks of this type is particularly distinctive: it is intergrown graphically with orthoclase and occurs in angular interspaces between the lath-shaped labradorite crystals. In this country this over-saturated type of microgabbro is well represented by the famous Whin sill of northern England,¹ and by the late-Carboniferous "quartz-dolerite" dykes, with east-west trend in the Midland Valley of Scotland. The sills in the Karroo, South Africa, where they so strikingly dominate the scenery, extend over an area of more than 10,000 square miles. They

¹ Holmes, A. and Harwood, H. F., "Age and Composition of the Whin Sill," *Min. Mag.*, xxi (1928), p. 493; and S. I. Tomkeieff, "Contribution to Petrology of Whin Sill," *Min. Mag.*, xxii (1929), p. 100.

are widely variable in the details of their composition and texture; but they closely resemble the plateau-basalts described below (p. 303), and include types like the Whin Sill and other over-saturated dolerites.¹

Usually hornblende is not found in microgabbros; but a brown amphibole in some cases identified as barkevikite, but in others as "basaltic hornblende" (*i.e.*, lamprobolite) does occasionally occur, as in the minverite type, described from the parish of St. Minver in Cornwall.

As regards texture the microgabbros and micronorites are very variable. Without question the most characteristic texture is the ophitic, and some petrologists will not apply the name dolerite unless the rock shows the special relationship between plagioclase and pyroxene implied by the term ophitic. The manner in which the large plates of pyroxene, as seen in thin section, enclose disorientated euhedral laths of plagioclase is usually interpreted as resulting from the prior crystallization of the latter; but evidence of the simultaneous growth of the two minerals is afforded by the variant described by H. H. Thomas as ophi-mottling. In this case the pyroxenes are ophitically related to *small* laths of plagioclase which they enclose, but they are themselves embedded in a plexus of *large* plagioclase crystals. In other specimens neither of the chief components is euhedral, though the plagioclase tends to develop its typical flattened habit, and the pyroxene tends to be prismatic; but owing to mutual interference during growth, both minerals are anhedral. If the term microgabbroic is used with a textural significance, it should surely apply to such rocks. As microgabbros grade into basalts with increasing fineness of grain, so the resemblance to basalts becomes more pronounced, with a tendency for the development of phenocrysts, particularly of plagioclase. Such rocks have been termed labradorite-porphyrries, but porphyritic microgabbro, or even feldsparphyric microgabbro are preferable names.

Although some microgabbros of all ages are ideally fresh, many others are highly altered as a consequence of their subsequent treatment. Participation in earth movements, a mild degree of metamorphism and, naturally, weathering may lead to the replacement of all the original components, in the manner already described for the gabbroic rocks. Saussuritization, albitization, chloritization and epidotization may all contribute to the conversion of the original pyroxene, labradorite, iron-ore, etc., into albite, chlorite, epidote, calcite, leucoxene and quartz, but some of these minerals, though of late formation, are not secondary in the sense of having replaced

¹ Walker, F., and Poldervaart, A., "Karoo Dolerites of the Union of S. Africa," *Bull. Geol. Soc. Amer.*, lx (1949), p. 591.

pre-existing minerals. Thus although chlorite is widespread as an alteration product of pyroxene (with epidote, calcite, etc., as by-products), it occurs also in sharply defined interstitial areas between plagioclase and clinopyroxene which show no trace of alteration, and in these cases is primary. Rather special interest attaches to the quartz in these rocks. As noted above, it is a widespread primary constituent, normally intergrown with alkali-feldspar; but in addition it occurs also in irregular grains closely associated with other obviously secondary minerals, and is evidently an alteration product. Thirdly, quartz may be xenocrystic (see below, p. 300). Clearly it would be a mistake to refer to such rocks, with secondary or xenocrystic quartz, as quartz-microgabbros, or quartz-dolerites. Such terms should apply only to rocks containing the *primary* mineral.

Although amphiboles are rare primary constituents of the rocks under consideration, they are widespread as alteration products. Thus late-stage alteration tends to convert the original pyroxene into actinolite, an early stage showing perhaps merely a fringe of acicular crystals, but the alteration is progressive until all trace of pyroxene is lost, and a pseudomorph of closely packed fibres of actinolite ("uralite") is produced. In the process of dynamothermal metamorphism a compact common hornblende is produced from the pyroxene in the conversion of microgabbro into hornblende-schist or amphibolite. It follows that as a result of these changes the original labradorite-pyroxene-ilmenite combination gives place to common hornblende, a less basic plagioclase and various minor constituents to strike a balance. Thus the rock, although chemically gabbroic, in mineral contents is, in a broad sense, more dioritic than gabbroic. To such rocks the term epidiorite¹ has been applied. Typical specimens occur among the sills in the South-West Highlands of Scotland.

III. THE BASALTS

The term "basalt" is one of the few rock names familiar to the "man in the street," and is one of the oldest in petrography. It is applied collectively to the fine-grained equivalents of the microgabbros and microrites. When fresh, basalts are black, minutely crystalline to compact rocks with high density. When exposed to weathering they assume a red or (more commonly) a green colour on account of the development of such secondary minerals as ser-

¹ "Epidiorite" (von Gumbel, 1874) is sometimes used in a wider sense, for example by J. D. H. Wiseman, who applies the term to all non-schistose rocks produced by dynamothermal metamorphism from basic igneous rocks, whether intrusive or extrusive. See "The Central and South-West Highland Epidiorites: A Study in Progressive Metamorphism," *Quar. Journ. Geol. Soc.*, xc (1934), p. 354.

pentines and chlorites. A further stage of alteration converts the basalt ultimately into a red bole.

Mineral Composition.

Microscopic examination of a typical basalt shows it to be composed essentially of plagioclase, generally within the range labradorite-bytownite, pyroxene and accessories, of which magnetite is the most obvious. When olivine is present in addition, the rock is termed olivine-basalt.

The plagioclase is typically labradorite or bytownite, but in some cases may be less calcic. It should be noted that certain American authorities separate andesites from basalts solely on the criterion of the kind of plagioclase: if less calcic than An_{50} , the rock is andesite, if more calcic, it is basalt. We feel that this is laying too much stress on one factor only: there are other characters that are equally significant, particularly the colour index and the presence or absence of olivine. The plagioclase may occur in two generations: as phenocrysts, often of relatively large size and commonly zoned, and as microlites of slightly more sodic composition.

From his studies of the Hawaiian lavas Washington¹ has suggested a classification of basalts according to the kind of feldspar present. He thus distinguishes oligoclase-basalt, andesine-basalt, labradorite-basalt and anorthite-basalt. It must be noted, however, that this principle can be applied only on the basis of *normative* feldspar for two reasons: firstly, the modal plagioclase is frequently strongly zoned; and secondly, there is an appreciable difference in composition between the phenocrysts, when present, and the microlites in the groundmass.

The pyroxenes may show significant differences in composition in basalts. In discussing the classification of the gabbros and norites considerable emphasis was laid on the respective rôles of the clinopyroxenes and orthopyroxenes. In the basalts, however, orthopyroxenes are usually absent as such; but their substance is actually present in clinopyroxene of special type, which is restricted to quickly-cooled rocks. At high temperatures a single kind of pyroxene—pigeonite²—is stable, and has the composition of diopsidic augite combined with a member of the enstatite-ferrosillite series.

There is one other factor which tends to suppress the orthopyroxenes: due to rapid chilling, olivine stands a better chance of survival than in a slowly-cooled rock, in which the olivine may be converted into orthopyroxene. The survival of the olivine in basalts must obviously affect the composition of the clinopyroxene. If

¹ Washington, H. S., "Petrology of the Hawaiian Islands," Part I, *Amer. Journ. Sci.*, v (1923), p. 468.

² In many publications pigeonites are referred to as enstatite-augites.

magnesium silicate is locked up in the olivine, it is not available for the formation of pigeonite: in olivine-rich basalts, therefore, common augite tends to fill the rôle of pigeonite. Other things being equal, however, in an olivine-free basalt, the pyroxene must be richer in magnesium, and pigeonitic.

Hornblende is rare in basaltic rocks, but biotite in small quantities is not uncommon. Among the minor constituents iron-ore is conspicuous, and is usually magnetite in small octahedra; but dendritic iron-ore often separates from the glassy base present in some basalts during the final stages of consolidation (Fig. 53, C). Apatite is plentiful, though usually the crystals are minutely acicular. The characteristic accessory of the acid rocks—zircon—is rarely seen in thin sections, but occasionally occurs as prominent red prisms, as in a well-known lava from Niedermendig in Germany. Secondary minerals are very varied. Olivine may show all stages of alteration to serpentine, iddingsite, chlorophaeite, limonite or rhombohedral carbonate; pyroxenes are replaced progressively by chlorite with or without calcite and epidote; while the plagioclases undergo decomposition as described above for the gabbroic and microgabbroic rocks. Further, on account of the conditions under which they are erupted, basalts (even some dyke-basalts), tend to be vesicular, and although in recent specimens the vesicles are gas-filled, in the course of time they become filled with such minerals as chalcedony, agate, chlorite, calcite and especially zeolites such as natrolite, phillipsite, heulandite and analcite.

Occasionally isolated and much-corroded quartz grains occur in basalts which otherwise appear quite normal. These crystals have been explained in two ways: (1) as having originated in an overlying acid magma, out of which they have sunk, under the action of gravity, into the underlying basic magma; (2) alternatively, they may be accidental xenocrysts, caught up during the uprise of the magma. L. Hawkes¹ has pointed out that it is unlikely that quartz crystals could sink into basaltic magma; but if this were possible, it would still be necessary to regard them as xenocrystic, for they were not formed from the magma in which they were ultimately incorporated. It is strictly incorrect to call such rocks quartz-basalts, as the quartz is not a normal constituent of the lava: they should be termed **quartz-xenocryst-basalts** or merely basalts containing quartz-xenocrysts. Examples occur among the Permian lavas in Ayrshire, and in England among the Exeter lavas of the same age;² but such xenocrysts are liable to occur in any basalt, of any age.

¹ Hawkes, L., *Quar. Journ. Geol. Soc.*, lxxx (1924), p. 112.

² Cf. W. G. Tidmarsh, "The Permian Lavas of Devon," *Quar. Journ. Geol. Soc.*, lxxxviii (1932), p. 741.

Textural Range.

In texture basalts are very variable: every gradation is represented between the vitreous—basalt-glass or **tachylyte**—and the holocrystalline. A large number of basalts contain a small quantity of glass forming minute angular patches between the crystals of the groundmass. It is prone to replacement by a green or yellowish substance known as palagonite, but when fresh is brown in colour



FIG. 118

Variolitic basalt, near Rhobell Fawr, Merionethshire. Skeletal microphenocrysts of plagioclase set in variolitic groundmass of feldspar and augite. Small vesicles are present in the lower part of the field.

and perfectly isotropic. Tachylyte normally forms a mere selvage to a thin dyke or sill, but if the chilling was sufficiently rapid, the whole of the dyke may be of tachylyte, as in Arran. Lava flows of tachylyte are rare, but do occur among the Hawaiian basalts.

Variolitic structure is apparently limited to basaltic rocks, and is equivalent to spherulitic structure in acid rocks. The essential feature is the occurrence of delicate brush-like, radially disposed fibres usually of feldspar, less commonly of pyroxene (Fig. 118).

This material may make up a large part of the rock, or it may be restricted to small interstitial patches, known as mesostasis. In the latter case it represents local "pockets" of late-stage material: it may be only one stage removed from the glassy condition, and

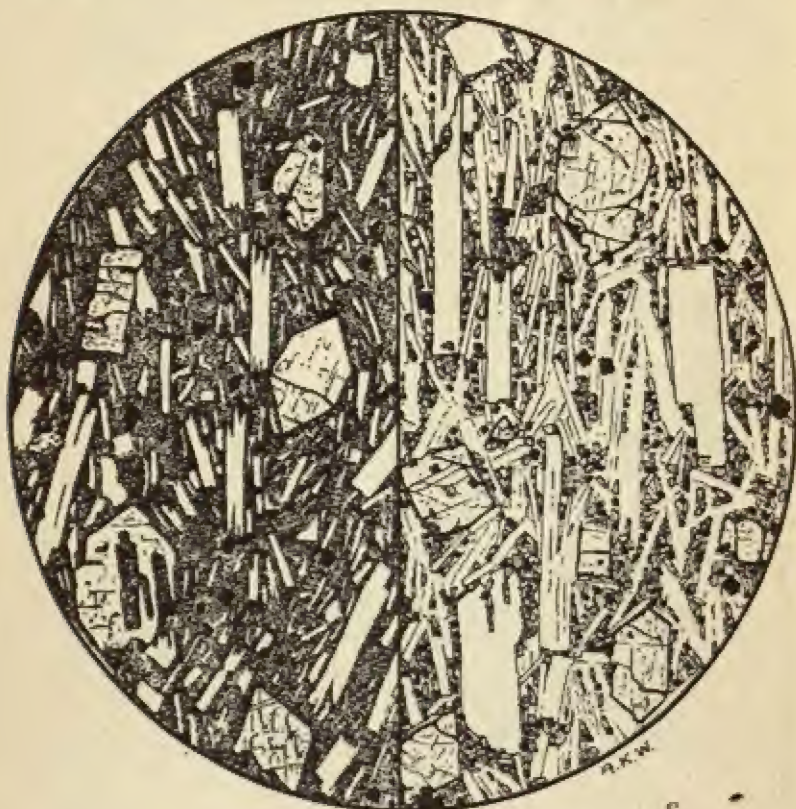


FIG. 119

Olivine-basalts from the Auvergne, France.

- Left:* Small phenocrysts of fresh olivine and plagioclase, many of the latter having forked ends. The groundmass is partially devitrified glass.
- Right:* Phenocrysts of olivine and plagioclase embedded in holocrystalline groundmass of lath-shaped plagioclase microlites, granules of augite and minute octahedra of magnetite. The texture is porphyritic, intergranular.

irresolvable under the microscope, but by analogy with the coarser-grained dolerites it is believed to represent an alkali-rich siliceous residuum.

From the point of view of the occurrence, or non-occurrence, of

phenocrysts, and of their relative sizes, three categories of basalt may be distinguished:—

- (a) aphyric—without phenocrysts. A more cumbersome term meaning the same thing is "non-porphyritic."
- (b) microphyric—with small phenocrysts; and
- (c) megaphyric—with large phenocrysts, greater than 2 mm.

The phenocrysts, when present, may consist of any of the main constituents—plagioclase, olivine, pyroxene or even magnetite. If the basalt is notably rich in olivine phenocrysts, it is chrysophyric; if correspondingly rich in plagioclase, it is feldsparphyric.[†]

Mode of Occurrence and Classification of basalts.

Basalts are, and apparently always have been, the dominant lavas the world over. They have been erupted over vast areas in many parts of the world, notably the Deccan (where they occupy approximately one-third of the total area of peninsular India, and locally reach nearly 6,000 feet in thickness), the Parana Basin in South America, the Snake River Plains in the U.S.A., and in the Thulean lava-field which includes Greenland, Iceland, the Faroes and the coastal areas of north-east Ireland and western Scotland. The basalts in these areas form vast dissected plateaux, and are frequently referred to as "plateau basalts." They were largely erupted from fissures rather than from central volcanoes. Elsewhere basalts have been erupted from cone-volcanoes of the central type, notably the Tertiary volcano of Mull in the Hebrides, and the active basaltic domes forming the Hawaiian Islands in the Pacific.

Rocks of identically the same compositional and textural range, and therefore also basalts, are widely distributed as dykes in these volcanic regions; they form suites of cone-sheets, volcanic plugs and less regular vent-intrusions in volcanoes of central type.

It will be realized that "basalt" is a "sack-name" covering a wide variation in composition and textural range. Detailed studies have led, therefore, to the description and naming of many types of basalt. One of the major current petrological problems concerns the nature of the magma or magmas from which they were all derived. It is agreed by all petrologists that in view of the world-wide distribution of basalts throughout all geological time, there must be a world-enveloping basaltic substratum. It is further agreed that it may well be stratified, and that these eruptives have, at different times and in different places been drawn from different levels, and therefore possess different potentialities as regards rock-types and differentiation products. Many petrologists have been led to believe, as a

[†] This term is more scientific than "big feldspar basalt," which has been applied to basalts of this type in the Scottish Tertiary Province.

consequence of this, that it is possible to recognize two basaltic magmas. The chemical differences between them are not spectacular; but their spacial distribution is significant. On the one hand there are the basalts (and their derivatives) derived from the basaltic substratum which underlies the ocean floors as well as the continental areas of the world; and on the other, a somewhat different basaltic assemblage which is restricted to the latter areas. Whether this is so or not, it is obvious that "pure" basalt, uncontaminated by possible

CHEMICAL ANALYSES OF TYPICAL BASALTS

	I. Plateau- basalt.	II. Plateau-basalt, Mull.	III. Picrite-basalt.	IV. Olivine- basalt, Hawaii.
SiO ₂ . . .	49.70	45.46	46.62	48.35
Al ₂ O ₃ . . .	14.24	15.04	8.68	13.18
Fe ₂ O ₃ . . .	3.66	3.48	2.04	2.35
FeO . . .	9.96	10.38	10.52	9.08
MgO . . .	6.82	8.12	20.86	9.72
CaO . . .	9.55	8.63	7.15	10.34
Na ₂ O . . .	2.64	2.59	1.41	2.42
K ₂ O . . .	0.70	0.45	0.28	0.58
H ₂ O . . .	— ¹	2.60	0.23	—
TiO ₂ . . .	2.23	3.06	1.71	2.77
P ₂ O ₅ . . .	0.33	0.26	0.14	0.34
MnO . . .	0.17	0.23	0.14	0.14
Other constituents	—	—	0.22	0.73
	100.00	100.30	100.00	100.00

- I. Plateau-basalt, average of forty-three analyses, quoted from R. A. Daly, 1933, p. 404.
 II. Average of three analyses of "plateau-basalts" from Mull, Scotland (Anal. E. G. Radley and F. R. Ennos), "Mull Memoir," 1924, p. 15.
 III. Picrite-basalt, average of three analyses, Hawaii, quoted from R. A. Daly, 1933, p. 397.
 IV. Average of 53 olivine-basalts, Hawaii, quoted from G. A. Macdonald, *Bull. Geol. Soc. Amer.*, lx (1949).

sialic material, should be found in the oceanic islands. The lavas of Hawaii are therefore of special significance.

In a recent study,¹ what is regarded as the Hawaiian "primary" magma-type is represented by olivine-basalt, an average chemical composition of which is quoted on p. 304. Expressed in terms of minerals it may be pictured as a porphyritic rock, with phenocrysts

¹ Macdonald, G. S., "Hawaiian Petrographic Province," *Bull. Geol. Soc. Amer.*, lx (1949), p. 1541.

of Mg-rich olivine, common augite, basic plagioclase (bytownite in some samples), embedded in a finely crystalline groundmass including a second generation of these minerals, differing slightly, but in predictable fashion, from the phenocrysts. The olivine granules are less magnesian, the clino-pyroxene is pigeonitic, and the plagioclase less calcic—usually labradorite. Magnetite is abundant. Among olivine-basalts there is little that is distinctive in this average rock: specimens closely approximating to this specification may be found among the basalts of Auvergne, the Carboniferous lavas of southern Scotland or the Hebridean lavas of Mull or Skye, for example.

A widely distributed rock-type evidently derived from such a parent olivine-basalt magma has been called **picrite-basalt** from its mineralogical similarity to (augite-) picrite (p. 336). Picrite-basalt is notably enriched in olivine, and correspondingly depleted in plagioclase. It is a cumulophyric rock formed by the concentration within the rock-body of olivine crystals derived from a very much larger volume of magma charged with olivine phenocrysts.

Another melabasalt, similar in origin to picrite-basalt (oceanite) is ankaramite; but this is, in effect, olivine-basalt enriched in clino-pyroxene.

Yet another cumulophyric basalt is correspondingly enriched in large plagioclase phenocrysts. These are very distinctive in hand-specimens, and are well represented in this country by the Carboniferous basalts of Markle type occurring in southern Scotland.

As the plateau-basalts are so phenomenally voluminous they have, as yet, been inadequately studied. Consequently averages based on too few analyses may give wrong impressions of the variation within a lava-field of the calibre of those noted above. Nevertheless such averages are available, and one of them is quoted on p. 304. In so far as it is representative, it suggests that, compared with the Hawaiian olivine-basalts, plateau-basalts are slightly more siliceous, equally aluminous, notably poorer (by half) in magnesia, though slightly richer in iron-oxides. While lime is reduced, soda is increased, and potash is doubled. In terms of minerals this suggests that olivine will be eliminated in favour of hypersthene or pigeonitic clinopyroxene, the plagioclase will be less calcic, and there may be (actually is) an alkali-rich residuum potentially quartz-bearing. Among rocks of medium grain-size, this magma-type is represented by the over-saturated dolerites forming the great sheet-irruptions of the Karroo (p. 296). Basalts of this type are frequently called "tholeiites"; but this term has been used in such a variety of senses without adequate definition, that its continued use is to be deprecated.¹

¹ Wells, A. K. and M. K., "On Magma Types and Their Nomenclature," *Geol. Mag.*, lxxxv (1948), p. 349.

THE ALKALI-RICH BASIC IGNEOUS ROCKS

1. COARSE-GRAINED TYPES

From the normal calc-alkaline gabbros, microgabbros and basalts we pass on to consider other groups which are equally basic, in the sense of being poor in silica, but which are relatively rich in alkalis. Some of these rocks are obviously closely related in essentials to the types considered above: in effect they are gabbros or olivine-gabbros with small but significant additions of soda-rich silicates such as analcite and/or nepheline. On the other hand some of these rocks have no affinity whatever with the normal gabbros and basalts. They are characterized by a high content of feldspathoids, and their affinities are evidently with the nepheline-syenites. In the following account we start with the alkali-rich rocks of essentially gabbroic type.

Essexite is one of the least satisfactorily defined of the basic rocks, and the name is applied to widely different mineral assemblages. The original essexite occurs in association with nepheline-syenites at Salem Neck,¹ Essex County, Massachusetts, and was defined in rather general terms by J. H. Sears. On re-examination the type-rock proved to have suffered contact metamorphism and metasomatism by an adjacent intrusion. Fundamentally essexite is a dark-coloured gabbroic rock in which a varied assortment of coloured silicates may accompany plagioclase, typically near labradorite, and small amounts of alkali-feldspar and feldspathoids. With regard to the last named, opinion seems to have been far from unanimous as to the amount of nepheline and/or analcite which should be present. Certain so-called essexites from Norway, described by Brögger, are not notably different from rocks which others would term olivine-gabbros: they contain no nepheline. Another well-known essexite from Rongstock in Bohemia contains only trifling amounts of that mineral; but in the Scottish essexites nepheline can be discovered in thin sections, although it has to be searched for. But although the mere list of minerals present does not suggest a highly distinctive rock-type, actually the Scottish essexites are well characterized, though it is textural quality rather than mineral content that is important (Fig. 120). Insofar as the

¹ Washington, H. S., "The Petrographical Province of Essex County, Mass.," *Journ. Geol.*, vii (1899), p. 53.



AKW

FIG. 120

Essexite, Crawfordjohn, Scotland.

Euhedral olivines and clinopyroxenes set in a groundmass of labradorite, nepheline (turbid through alteration), clear interstitial analcite, magnetite, and apatite, in some instances, cored. Note the zonal inclusion of small plagioclases in the titanite; the twinning of the latter; and euhedral basal sections of nepheline (centre, slightly left).

rocks consist chiefly of labradorite, titanaugite, olivine, apatite and ilmenite, they are like many another olivine-gabbro; but tucked away in the interstices between the laths of labradorite will be found patches of nepheline, of unmistakable analcite and of orthoclase. Further, the olivines are fresh and clear, the titan-augites particularly well-formed, and at once attract attention in the hand-specimen. These strongly porphyritic essexites are well represented by the Crawfordjohn rock well-known to many Scotsmen, as it is a favourite "curling-stone."¹

By increase in the amount of nepheline essexite passes into theralite, described below.

Teschenite (Hohenegger, 1861) is so named after the original locality, Teschen, in Silesia. In mineral composition teschenite is in general like gabbro, but differs in containing analcite as an essential constituent. The type is therefore defined as consisting essentially of basic plagioclase, near labradorite, clinopyroxene (usually titan-augite), and analcite, together with the usual gabbroic accessory minerals. Commonly barkevikitic amphibole occurs in close association with the titanaugite, and biotite often occurs in small quantity.² Olivine is not constantly present, and is therefore omitted from the definition of the type; when olivine does occur, the rock is **olivine-teschenite**.

In texture teschenites vary widely: they may be ultra-coarse—teschenite-pegmatites, coarse to medium—the majority hover on the brink between gabbroid and doleritic, while some are notably finer than the main body of the intrusion, of which they form a part. Such have been called teschenite-basalts, but as this suggests a rock half-way between teschenite and basalt, **microteschenite** is a more appropriate name.

In Scotland teschenitic rocks form large, often differentiated sills, such as the Inchcolm sills which forms the island of that name in the Firth of Forth (see map, Fig. 140), and the well-known sheet exposed at Salisbury Crags, Edinburgh (Fig. 61). Certain of the Scottish teschenites contain some alkali-feldspar in addition to the labradorite. Usually it does not amount to more than 10 per cent of the whole rock, but it is a significant constituent, and Johanssen considers that they should be given a distinctive name, and suggests Glenmuirite, from the locality in Central Ayrshire where the exposures of "teschenite" in the Lugar Sill occur.

¹ Scott, A., "The Crawfordjohn Essexite and Associated Rocks," *Geol. Mag.*, 1915, p. 458.

² Tyrrell, G. W., "Classification and Age of the Analcite-bearing Rocks of Scotland," *Geol. Mag.*, ix (1923), pp. 249-60; F. Walker, "Notes on the Scottish and Moravian Teschenites," *Geol. Mag.*, ix (1923), pp. 242-49.

³ Campbell, R., and Stenhouse, A. G., *Trans. Geol. Soc. Edin.*, ix (1907), p. 121.

Crinanite, named after a Scottish locality by J. S. Flett (1911) is also a type of analcite-gabbro, closely related to teschenite: it is so close, in fact, that there is little doubt that both names have been misapplied—crinanites have been recorded as teschenites and vice versa. Both names are widely used in official Survey publications. The original crinanites were collected from (presumably) Tertiary dykes in the neighbourhood of Loch Crinan, Argyllshire. Stress was laid, in the description, on their relative fineness of grain and perfect ophitic texture. We would prefer to stress facts of mineral composition, however, and to cover textural variation by the use of appropriate qualifiers. Chemically crinanites are closely similar to plateau-basalts; mineralogically they are close to teschenites, but are richer in coloured silicates and poorer in analcite and other zeolites. The colour index of the type-rock is rather less than 50, with olivine somewhat in excess of titanaugite (22 and 19 per cent respectively). Analcite and other zeolites amount to only about 2 per cent. Walker has suggested that there is room for both teschenite and crinanite in our nomenclature, and that the distinction should be made on the basis of the amount and rôle of zeolites. If analcite and other zeolites are restricted to angular interspaces between the other dominant constituents, the rock, other things being equal, of course, is crinanite; but if they not only fill the interstices but also cause analcitization of the adjacent plagioclases, the rock is teschenite.¹

So far as texture is concerned, crinanites should be brought into line with teschenites, and according to their grain size we may distinguish crinanites (coarse grain) from microcrinanites (medium grain), while the fine-grained equivalent of these types is analcite-basanite (see below, p. 320).

An allied type in which nepheline displaces analcite is **theralite**, consisting of plagioclase within the usual gabbroic range, clinopyroxene, and nepheline, together with sundry accessories. Rosenbusch proposed the name (1887) for the plutonic representative of nepheline-tephrite—a fine-grained volcanic rock consisting of this mineral assemblage. The rock originally described under this name by J. E. Wolff from the Crazy Mountains, Montana, does *not* correspond with nepheline-tephrite as it is rich in orthoclase, and must be classed as malignite.

Typical theralites are not common rocks, but specimens closely agreeing with Rosenbusch's conception of what a theralite should be have been described from the Cordilleras of Costa Rica, the Bohemian alkali province and from Scotland. Perhaps the best known theralite, which figures in many teaching collections, comes from

¹ Walker, F., "The term 'Crinanite,'" *Geol. Mag.*, lxxi (1934), p. 122.

Duppau in Sudetenland. Equally typical are certain late-Carboniferous examples occurring in Ayrshire, notably in the Lugar composite sill, in which the theralite is accompanied by teschenite. In the Scottish theralite type titanaugite is the most abundant component (35 per cent), while labradorite and nepheline occur in approximately equal amounts (16 per cent each in the Lugar theralite). An amphibole, barkevikite in the Scottish rocks, biotite and olivine may all be present in varying amounts, but are not covered by the definition. If olivine is present in significant amounts, by analogy with the fine-grained equivalents another name should be used, comparable with nepheline-basanite, though there are many precedents for calling such a rock **olivine-theralite** by analogy with, for example, basalt and olivine-basalt.

Kylite (G. W. Tyrrell, 1912),¹ is an olivine-rich melatheralite which is correspondingly poor in nepheline. The name was taken from the Kyles of Bute in Scotland.

It is perhaps appropriate to introduce at this point the unique associate of teschenite and theralite in the Lugar sill, named **lugarite** by Tyrrell (1912). In the hand specimen lugarite is distinctive by reason of the abundant long narrow prisms of barkevikite and titanaugite which are embedded in a greyish-green matrix. Originally the latter was recorded as chiefly altered analcite, with about 10 per cent of altered labradorite and traces of nepheline; but the examination of fresh material obtained by boring has proved the matrix to consist largely of nepheline, *not* analcite. Therefore lugarite is a barkevikite-theralite. Euhedral barkevikite and strongly pleochroic titanaugite are shown to particular advantage in this rock, while apatite in profusion, and ilmenite in an advanced stage of alteration to leucoxene (Fig. 54) are noteworthy accessories.

In the types so far considered emphasis has been laid on the essentially gabbroic nature of the rocks, and the subordinate, though very significant, rôle of the alkali-rich silicates. The next group consists of rocks which, though equally basic, are definitely not gabbroic, as they contain no plagioclase—an essential constituent of the latter group. The common feature throughout is the occurrence of nepheline, and the rocks evidently lie at the basic end of the nepheline-syenite range. Some of them, in spite of their very low silica percentage, are leucocratic rocks and possess syenitic affinities; but others are melanocratic, and at least in superficial appearance find their proper place among the basic plutonites.

Although not quite feldspar-free (the type-rock contains 2 per cent of albite), **monmouthite** may be considered here. Nepheline

¹ Tyrrell, G. W., in *Trans. Geol. Soc. Glasgow*, xxi (1948), p. 15.

makes up three-quarters of the whole rock and is accompanied by cancrinite associated significantly with calcite, while the coloured silicate is a bluish-green amphibole of the hastingsite type. This is the really distinctive feature of monmouthite.

Urtite (Ramsay, 1894), is named from the type-occurrence in the parish of Lujavr-Urt in the Kola Peninsula, U.S.S.R. No feldspar occurs in this type, but nepheline makes up 85 per cent. The colour index is thus only 15. As might be expected the silica percentage is very low (45), while the alumina is extraordinarily high, reaching nearly 30 per cent, and the total alkalis amount to 20 per cent (16 per cent Na_2O).

Ijolite (Ramsay and Berghell, 1891), with a colour index of about 50 has a typical basic appearance though there is nothing gabbroic in its mineral composition (Fig. 121). Half the rock is nepheline, a sodic clinopyroxene is nearly as abundant, while the accessories include apatite, sphene, cancrinite and occasionally melanite garnet. Ijolites occur in the closest association with such typical nepheline-syenites as foyaïtes, for example at Spitzkop, Sekukuniland, South Africa, and in other alkali complexes, including naturally the type occurrence at Ijo in Finland. As ijolite is a combination of nepheline and clinopyroxene with accessories, it is the mineralogical equivalent of nephelinite among the basic feldspathoidal lavas.

Finally, with increasing coloured minerals and less nepheline, ijolite grades into the end member of this line of variation—**Jacupirangite**, described by O. A. Derby (1891) from Jacupiranga in Brazil. In an average specimen nepheline may make up a quarter of the rock. A sodic clinopyroxene, usually aegirine as in most of this range of rock types, and the usual accessories make up the rest. In some specimens the quantity of nepheline decreases as the colour index rises until ultimately jacupirangite grades into a type on the borderline of the ultramafic pyroxenites. The fine-grained equivalent of jacupirangite would be a melanocratic nephelinite: actually a fine-grained lava from Ankaratra, Madagascar, has the chemical composition of jacupirangite. It was given a local name¹ by Lacroix, but is in effect a melanocratic olivine-nephelinite, containing perovskite and, in some facies, melilite as well.

The third group of the alkali-rich basic plutonites are essentially rich in potassium, as shown by the occurrence of orthoclase, or, in the under-saturated types, of pseudoleucite.

Shonkinite forms a large part of the Shonkin Sag laccolite in the Bearpaw Mountains, Montana. Weed and Pirsson first used the name to signify a coarse-grained basic rock, with excess of dark over

¹ Ankaratrite (Lacroix, 1916).

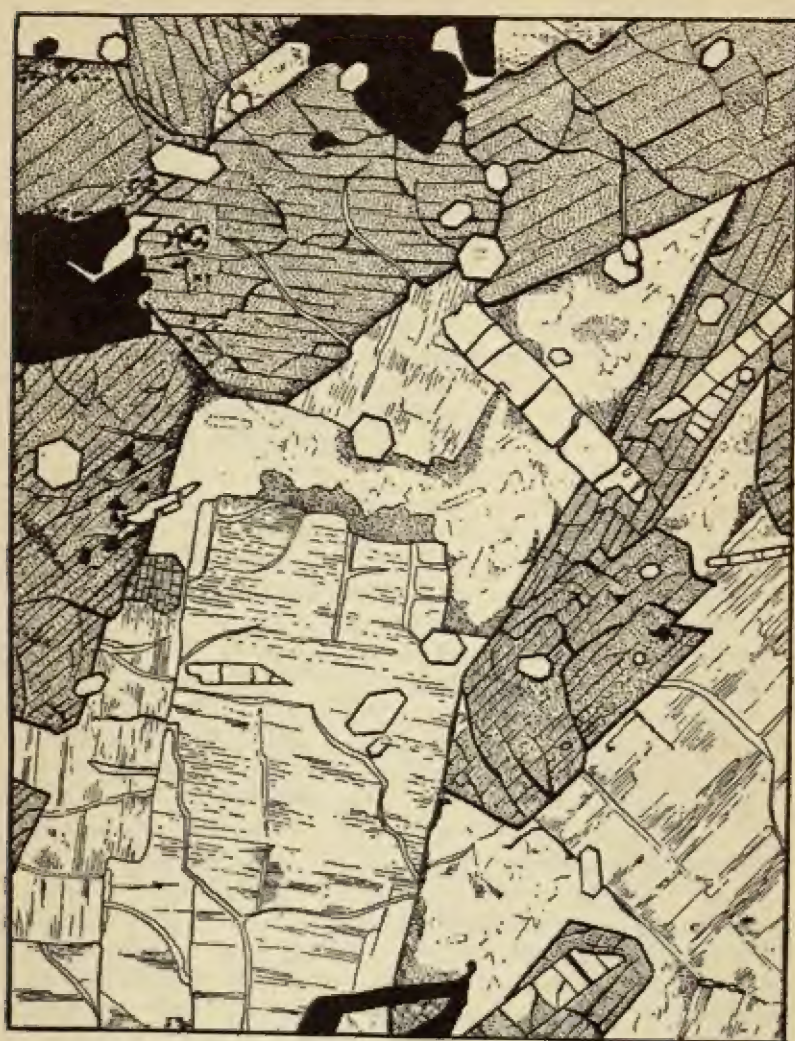


FIG. 121

Ijolie, Neudorf, Schreckenstein, Austria. The chief components are titanite and nepheline, both in well-formed crystals, especially the latter. Nepheline is interstitial to these, and is partly altered to a zeolitic aggregate. Apatite and iron-ore are prominent accessories. The nephelines are traversed by canal-like fractures, while the cleavage is accentuated by incipient alteration.

light minerals, and with orthoclase associated with clinopyroxene.¹ In the type-rock the chief components are augite, orthoclase, olivine and biotite in order of abundance. In the same rock a little nepheline does occur, but only as an accessory, and the name shonkinite is used without qualification when nepheline is absent, but otherwise, "nepheline-shonkinite." The field relations make it quite clear that the shonkinite at Shonkin Sag represents a part only of the magma from which it was formed, and that its high content of dark silicates was due to crystal-accumulation. The only other rocks which resemble shonkinite in mineral contents occur among the lamprophyres.

Another named type which appears to be all but synonymous with nepheline-shonkinite is **malignite** (Lawson, 1896), named from the Maligne River in Ontario. As in shonkinite, clinopyroxene is the most abundant mineral making up roughly half the rock; orthoclase and nepheline are about equal in amount, while biotite, apatite and sphene are common accessories. If both names are to be retained, the only basis of distinction is in the rôle of the nepheline. If it has the status of an accessory only, say a maximum of 5 per cent, the rock may be appropriately termed nepheline-shonkinite; but if nepheline is essential (more than 5 per cent), it is malignite.

A malignite of particularly striking appearance in thin section is illustrated in Fig. 122. Two feldspathoids, nepheline and a member of the hauyne-nosean group, accompany orthoclase. Both the former are perfectly euhedral, the nephelines being fresh, save for incipient alteration which tends to emphasize the prismatic cleavage. The hauynes on the other hand are turbid, with blue-black centres. They are of early formation and are embedded in all the other components except olivine. The latter occurs in small crystals, a little serpentinized, and very subordinate in amount to aegirine-augite, which has deeper green, strongly sodic outer zones. Magnetite, chiefly in octahedra, and apatite, in prisms with dark cores, are the chief accessories. It may be noted that four of these components show perfect hexagonal shapes in suitably orientated sections. The orthoclase forms large poikilitic plates enclosing all the other components.

A variety of malignite rich in melanite garnet occurs along the banks of the Ledmore River in Assynt, Scotland, and was named ledmorite by Shand, who later withdrew the term in favour of **melanite-malignite**. Locally the content of melanite rises as high as 25 per cent.

¹ Pirsson, L. V. and Weed, W. H., *Bull. Geol. Soc. Amer.*, vi (1895), p. 389; also Pirsson, L. V., "Petrography . . . of the Highwood Mountains, Montana," *Bull.* 237, *U. S. Geol. Surv.*, 1905, p. 97.

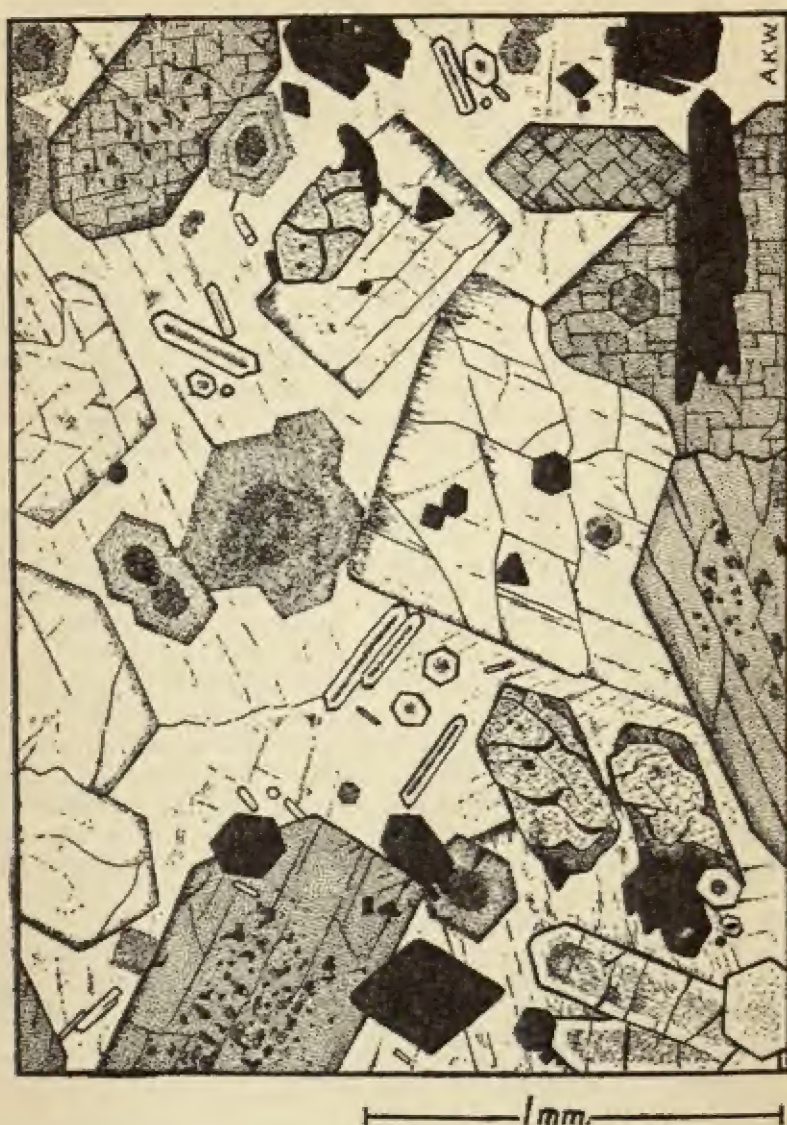


FIG. 122

Hauyne-olivine-malignite, Katzenbuckel, Odenwald. Aegirine-augite, stippled olivine (three small crystals); hauynes, turbid, showing zoning; nepheline, euhedral, clear; orthoclase, poikilitic, clear; apatite, several "cored" magnetite, euhedral.

Two undersaturated types are related to the above in mineral composition—fergusite and missourite.

Fergusite (Pirsson, 1905), is another type described from the Highwood Mountains, Montana. It is chemically similar to shonkinite, but is ideally feldspar free, with leucite replacing orthoclase. As is normally the case with deep-seated rocks, the leucites have inverted to the mixture of nepheline and orthoclase termed pseudo-leucite. The latter makes up half the rock (65 per cent in the type-rock), while aegirine-augite is the chief coloured silicate, and magnetite the most abundant accessory. Fergusite occurs also in the Roman volcanic province, but is known only in the form of ejected blocks, associated with italite (see below) in agglomerates. Recently a stock of fergusite has been discovered near Tashkent in the U.S.S.R. Again pseudoleucites make up about half the rock, which chemically is characterized by low silica (48) but high potash (9.5 per cent). Fergusite is evidently the equivalent of the basic lava, leucitite, and there are no doubts as to its affinities: it lies at the basic end of the leucite-syenite range.

Missourite (W. H. Weed and L. V. Pirsson, 1896), also comes from the Highwood Mountains, Montana, and is obviously related to fergusite, but is more melanocratic. Roughly half the rock consists of augite, olivine is also an important constituent, magnetite is the chief accessory, but leucite has dwindled in amount to some 15 per cent. Missourite is an olivine-melafergusite and is the mineralogical equivalent of olivine-leucitite among the basic lavas.

A connecting link between the coarse- and fine-grained rocks of this composition is afforded by a minor intrusive type termed "missourite-porphry" by R. A. Daly (1912), which he discovered in British Columbia. In the interests of consistency we would prefer to call it porphyritic micromissourite.

Some doubt attaches to the status of **borolanite**, named by Sir J. J. Teall (1892) from Loch Borolan in the North-West Highlands of Scotland: but the type is nevertheless an interesting one. The dominant constituents are orthoclase, "pseudo-leucite," melanite, green biotite and pyroxene. Plagioclase (oligoclase) and nepheline are subordinate, while the accessory minerals include sphene and purple fluorite. The typical rock is a granular aggregate of orthoclase, melanite and biotite, containing polyhedral to spherical light-coloured patches, which under the microscope resolve themselves into aggregates of orthoclase and nepheline, the latter altered in large part into "pinite" and zeolites. These are the supposed pseudo-leucites. The orthoclase also contains polygonal patches of a very delicate intergrowth of the zeolite, mesolite and orthoclase

	I. Shonkinite.	II. Borolanite.	III. Missourite.	IV. Essexite.	V. Theralite.	VI. Kentallenite.
SiO ₂	46.73	48.19	45.08	44.70	47.67	48.00
Al ₂ O ₃	10.05	18.52	15.68	14.50	18.22	12.52
Fe ₂ O ₃	3.53	4.51	4.52	2.95	3.65	8.74
FeO	8.20	1.68	3.09	8.35	3.85	—
MgO	9.68	1.12	4.68	7.82	6.35	15.26
CaO	13.22	10.29	11.75	11.25	8.03	7.94
Na ₂ O	1.81	3.44	2.38	4.10	4.93	3.11
K ₂ O	3.76	8.05	8.42	1.71	3.82	2.68
H ₂ O	1.24	3.45	0.88	1.71	3.35	1.36
TiO ₂	0.78	1.75	1.36	2.34	n.d.	0.22
P ₂ O ₅ and other constituents .	1.93	—	2.37	0.82	0.28	—
	100.93	101.00	100.21	100.25	100.15	99.83

I. Shonkinite, Square Butte, Highwood Mts., Montana. L. V. Pirson, *Bull. Geol. Soc. Amer.*, vi (1895), p. 389.

II. Borolanite, Am Meallan, Loch Borolan, Ross. W. Campbell Smith, *Geol. Mag.*, 1909, p. 154.

III. Missourite, Type B, Italy. Washington, *Amer. Journ. Sci.*, xiv (1927), p. 33.

IV. Average of two Scottish essexites; from G. W. Tyrrell, *Geol. Mag.*, lx (1923), p. 254.

V. Theralite, Three Peaks, Crèzy Mts., Montana. Anal. G. Schneider, *Bull. 150 U.S. Geol. Surv.*, 1898, p. 201.

VI. Kentallenite, Kentallen, near Ballachulish, Argyll. J. J. H. Teall, *Rep. Geol. Surv.*, 1896 [1897], p. 22.

which are possibly pseudomorphous after sodalite. Shand has questioned the identity of the rounded white spots in the type-rock with the undoubted pseudo-leucites of other localities, in spite of their close resemblance in general appearance, chemical and mineral composition.¹

II. BASIC ALKALI-RICH IGNEOUS ROCKS OF MEDIUM GRAIN-SIZE

On account of their comparative rarity there is little point in attempting a full systematic description of the medium-grained equivalents of the rocks considered above. Many of them would be hypothetical, others have already been mentioned in passing. It is known, for example, that rocks of the teschenitic mineral association vary in grain-size between coarse and fine. As we have applied the prefix "micro-" systematically to rocks in the medium grain-size group (to avoid doubling the number of rock-names used), by comparison with the plutonites defined above, the meanings of such terms as microteschenite, micromissourite, etc., are self-evident. **Microteschenite** is, in effect, an analcite-microgabbro, belonging to the medium grain-size group in virtue of its degree of crystallinity, and in mineral composition matching the type teschenite sufficiently closely as to justify using its name.

As an example one rock in this group is illustrated in Fig. 123. It is a dark-coloured compact rock, in the hand specimen very different from the coarse ijolite with which it is associated in the field, and which shows prominent lustrous prisms of aegirine, lemon yellow cancrinite, and reddish nepheline. In thin section, however, the **microijolite** is seen to have just this composition, the several components forming an interlocking granular mosaic: even the abundant apatite is anhedral. In addition to the grains of brilliant green aegirine, this mineral occurs also in the form of minutely acicular crystals, regularly orientated in parallel swarms. The nephelines occasionally show "ghost-crystals" outlined with globular inclusions. The most significant accessory is calcite, surrounded with cancrinite forming a reaction rim of radially disposed flakes.

Reference may be made at this point to the albite-microgabbros, commonly called **albite-dolerites**. In their general mineralogical characters they simulate normal dolerites, but the place of the labradorite is taken by albite. There has been much discussion as to whether the albite is primary or secondary. In many cases it is demonstrably secondary, as the feldspars are charged with lime-rich minerals in granular aggregates often concentrated near the centre

¹ Shand, S. J., *Trans. Geol. Soc. Edin.*, ix (1909-10), pp. 202 and 376.



FIG. 123

Microijolite, Spitzkop, Sekukuniland, South Africa. Aegirine, stippled; nepheline clear, but zoned occasionally; apatite, with "varnish" of cancrinite (*top, left*); calcite with reaction rim of cancrinite (*bottom, right*).

of the crystal. Further, the pyroxene is often more or less altered to secondary amphibole or chlorite. If, however, the albite is primary then we are dealing with a distinctive rock-type and a special name is justified: it might even be argued that albite-microgabbro or albite-dolerite is not sufficiently distinctive, as we have sepa-

rated albite from the plagioclases for purposes of classification, and plagioclase is essential in gabbro and therefore in microgabbro. One such rock has indeed received a special name, and has already been mentioned. **Minverite**,¹ named from the parish of St. Minver in Cornwall, is fundamentally an albite-microgabbro, but there are also sufficient special features to justify the special name. It contains barkevikite in addition to pyroxene, while biotite also is prominent.

III. THE FINE-GRAINED ALKALI-RICH BASIC IGNEOUS ROCKS

In earlier editions of this book the rocks in these categories were referred to collectively as "alkali-basalts." But as this name has been used in a much more restricted sense by Rosenbusch² for a division of his "trachydolerites," it has been abandoned.

The most distinctive features of these rocks are their fine-grain, their general resemblance to basalts, and on the mineralogical side the occurrence in them of essential feldspathoids. For convenience we include corresponding types characterized by the presence of analcite and kalsilite, for though strictly speaking neither mineral is a feldspathoid, both are under-saturated.

The classification of these rocks is effected, firstly, according to the kind of feldspathoid or allied mineral present; secondly, whether feldspar is present or absent; and thirdly, whether the rock is olivine-bearing or olivine-free.

The essential features of the main types are shown in tabular form on page 320. The kalsilite-bearing types are described separately.

Rather more explanation than usual is necessary to justify, or at least explain, the choice of names. The only thing to be said in favour of some of them is that they are long-established terms, so well entrenched in geological writings that there is little hope of displacing them, though they may be illogical and misleading.

~~The~~ tephrites and basanites are comparable with basalt and olivine-basalt respectively. **Tephrite** may be defined therefore as a fine-grained basic igneous rock, occurring either as a lava flow or a minor intrusion, and composed essentially of plagioclase of the kind occurring in normal basalts, together with clinopyroxene and/or amphibole or mica, in association with nepheline, leucite or analcite. According to the dominance of one or other of the feldspathoidal minerals, it is possible to distinguish between nepheline-tephrite, leucite-tephrite and analcite-tephrite.

The addition of olivine to this mineral association should logically give olivine-tephrite; but the term **basanite**, introduced by A.

¹ Dewey, H. and Flett, J. S., *Geol. Mag.*, 1911, p. 209.

² See Osann-Rosenbusch, *Elemente der Gesteinlehre*, 1923, p. 455.

Brogniart (1813) is firmly established and popular. Again it is possible to recognize nepheline-basanite, leucite-basanite—probably the commonest of all these lavas—and analcite-basanite. Further detailed definition is unnecessary.

In the feldspar-free types the resemblance to basalts no longer holds and the similarity arising from the presence of nepheline or leucite is less significant than the difference resulting from the elimination of plagioclase. In no sense can these rocks be classed

ESSENTIAL FEATURES OF THE MAIN TYPES OF FINE-GRAINED
ALKALI-RICH BASIC IGNEOUS ROCKS

	<i>Without Olivine</i>	<i>With Olivine</i>
Leucite Series	<i>Containing Feldspar</i>	
	LEUCITE-TEPHRITE	LEUCITE-BASANITE
	<i>Types without Feldspar</i>	
	LEUCITITE	OLIVINE-LEUCITITE
Nepheline and Analcite Series	NEPHELINITE	OLIVINE-NEPHELINITE
	<i>Containing Feldspar</i>	
	NEPHELINE-TEPHRITE ANALCITE-TEPHRITE	NEPHELINE-BASANITE ANALCITE-BASANITE

as feldspathoidal *basalts*: one of the fundamental constituents of basalts is absent. The names commonly used for the combination nepheline and pyroxene, and leucite and pyroxene, with accessories are, as stated above, most illogically chosen. They are **nephelinite** and **leucitite** (Fig. 124) respectively; and by analogy we may add the hypothetical **analcitite** to complete the trio. It should be noted that although "albitite" is monomineralic, consisting solely of albite; and "olivinite" is a pure olivine rock; and "diaggite" one consisting essentially of diallage only, yet "nephelinite" is not the monomineralic nepheline-rock, but as shown in the table, is a basic nepheline-bearing lava, containing neither plagioclase nor olivine. Accepting "nephelinite," and by analogy, "leucitite" and "analcitite" in this sense (though under protest, for it is wholly illogical),

the addition of olivine should give "olivine-nephelinite," "olivine-leucitite," and "olivine-analcitite"—not "nepheline-basalt," etc., though unfortunately the latter term is still advocated in some quarters.

In all those rocks in this group which contain leucite the latter, by reason of its distinctive optical properties, is most easily identified.

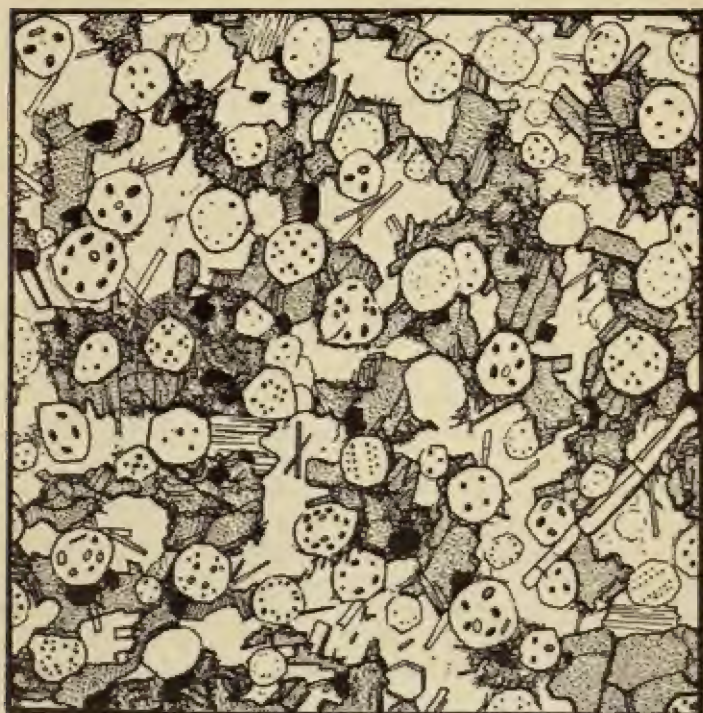


FIG. 124

MKW

Leucitite, Capo da Bove, near Rome.

Small euhedral leucites, clinopyroxene, a little mica, accessory apatite and magnetite. The groundmass is colourless glass.

It commonly occurs in two generations, the phenocrysts in many instances being easily identified in hand specimens, by their icositetrahedral shape and off-white colour. The first generation leucites show their characteristic complicated twinning, but the smaller individuals in the groundmass are usually singly refracting. The nepheline, on the other hand, may be much more difficult to identify. In the most favourable circumstances the characteristic hexagonal basal sections and rectangular vertical sections are very distinctive

(Fig. 125). But in other cases the relationship between the nepheline and other minerals is different: the former may occur in disseminated grains, largely interstitial to the other components of the groundmass, and can be proved only by microchemical tests.

Analcite seems to be restricted to the groundmass of those lavas which contain this mineral. Although by analogy with the nephelinic and leucitic types we suggest the recognition of four types named above, only one of them, **analcite-basanite**, seems to have been so far discovered. The identification of small quantities of analcite in fine-grained rocks demands skill and very careful manipulation of the microscope: there are other colourless minerals with such closely similar optical properties that special tests are really needed to establish the identity of the mineral with complete certainty. A typical example occurs at Calton Hill, Derbyshire. It has the appearance of an ordinary olivine-basalt on superficial examination, but the analcite is present, forming small rounded areas (ocelli), and in the aggregate is estimated to form some 14 per cent of the rock.¹

The nephelinic and leucitic lavas usually occur independently, in separate areas. Thus in Turkana² and areas on the east of the great Rift valley in Central Africa, the igneous rocks which cover a wide range of types—from acid to almost ultrabasic—are sodic; but on the western side, they are potassic, leucitic types. The sodic lavas belonging to the group under consideration include nepheline-tephrites, nepheline-basanites, analcite-basanites, nephelinites and olivine-nephelinites, some of which are probably the finest examples of their kind (Fig. 125). The striking **nephelinite** illustrated is noteworthy for the spectacular display of euhedral nephelines, large titanaugites with pale green outer zones, the relationship between the large plates of poikilitic phlogopite and the augites, and the poikilitic sphenes. Attention is drawn to certain textural features, notably the evidence for late growth of the phenocrysts: the outer zones of the augites enclose numbers of small nephelines poikilitically.

Leucitic lavas are characteristic of, and best known from the Roman volcanic province, and at one time were thought to be restricted to it; but they have now been recorded from a number of widely separated localities: the Leucite Hills in Wyoming, Uganda and Tanganyika, the West Kimberley District in Western Australia, the Dutch East Indies and Antarctica. In addition to more normal

¹ Tomkeieff, S., "The Volcanic Complex of Calton Hill (Derbyshire)," *Quar. Journ. Geol. Soc.*, lxxxiv (1928), p. 715.

² Campbell Smith, W., "Petrographic Description of Volcanic Rocks from Turkana, Kenya Colony . . .," *Quar. Journ. Geol. Soc.*, xciv (1938), p. 507.



FIG. 125

Nephelinite, summit of Lodwar Hill, northern Turkana, Kenya Colony.

Brit. Mus. ref. No. 60.1936.1333.128.

For description see text, p. 322. Pyroxene, stippled; magnetite, black; sphene, heavy stipple. Phlogopite with cleavage indicated. There are two generations of pyroxene.

types Uganda has provided unique lavas containing the silicate, kalsilite. Many of these rocks are fitted into a scheme of classification with some difficulty, and every new discovery results in new rock-names.

Although not a new discovery, *italite* (Washington, 1920),¹ remains a most puzzling rock-type. It is not known in place, but occurs among the blocks in an agglomerate in the Alban Hills near Rome. It consists almost entirely of large leucite crystals held together by a small amount of whitish material believed to be altered glass. This is most significant material, for if it is actually glass, it proves the rock to be a porphyritic lava consisting solely of phenocrystal leucites. But whatever the depth at which it originated, *italite* is evidently a *cumulophyric* rock, consisting of sorted crystals, which on account of their low specific gravity must surely have accumulated at the roof of the magma chamber. As we have argued for other cumulophyric rocks, anorthosite for example, such an accumulation could be neither intruded nor extruded, but could be disrupted by volcanic explosions, as has happened in this solitary case on record.

From the West Kimberley area, Western Australia,² four distinctive lava-types, connected by intermediate varieties, have been described. The common feature throughout the series is the dominance of leucite, varying from 20 to 60 per cent in different specimens; the complete absence of feldspar is an important feature, while the associated coloured minerals show considerable variety. One type, carrying up to 20 per cent of phlogopite, is obviously related to the leucitic lavas of the Leucite Hills, Wyoming³ (p. 255). A second variety is characterized by phlogopite accompanied by a manganese-amphibole near kataphorite in composition; a third contains leucite and this amphibole; a fourth contains diopside prisms and pseudomorphs after olivine, and is therefore an olivine-leucitite. The most striking thing about these rocks is the ~~fact~~ that, although they are claimed to be "the most richly leucitic rocks in the world," the preservation of the leucite is simply an accident of their cooling history, for they contain plenty of silica to have formed sanidine to the exclusion of leucite, if they had consolidated under other conditions. The silica needed for this conversion is present in the glassy base. The magma from which these rocks were

¹ Washington, H. S., "Italite, a new Leucite Rock," *Amer. Journ. Sci.*, i (1920), p. 33.

² Wade, A. and Prider, R. T., "The Leucite-bearing Rocks of the West Kimberley Area, Western Australia," *Quar. Journ. Geol. Soc.*, xcvi (1940), p. 39.

³ Cross, W., "The Igneous Rocks of the Leucite Hills, etc.," *Amer. Journ. Sci.*, iv (1898), pp. 126, 134 and 149.

formed was exceptional in several respects, however. The amount of Ti is very high throughout—much of it is present in the phlogopite and other dark minerals, but some appears as rutile, which reaches 6 per cent in one type. The content of barium also is notably high.

These rocks are difficult to place. So far as their actual mineral composition is concerned, they must be regarded as basic feldspathoidal lavas of the leucitite type; but potentially they are nearer to leucitophyre, and the one feature which "tips the balance" is the essential basicity of the magma from which they crystallized.

As previously noted, one of the rock-types described by Cross from the Leucite Hills, Wyoming, may be considered here, though its systematic position is, if possible, even more debatable. It is linked to the other leucitic lavas of the district by the occurrence of phlogopite, second in importance, however, to diopside which makes up nearly half the rock. Apart from minor accessories, among which perovskite is noteworthy, these are the only minerals present: no actual crystals of leucite occur, but one-third of the rock is leucite-glass, *i.e.*, potential leucite. Thus chemically at least, the rock¹ is the equivalent of missourite among the coarse-grained feldspathoidal rocks. In the volcanic region of Central Africa feldspathoidal lavas of diverse types occur. In some regions they are strongly potassic; elsewhere they are just as strongly sodic. The potassic suite includes definitely ultrabasic types, invariably feldspar-free, notably rich in mafic minerals and certain minor constituents including TiO_2 , BaO and SrO . As might be expected, leucite is widespread; but some types contain the less siliceous kalsilite, first discovered in these rocks, and so far known only from this region. The rock-type named **katungite** by Holmes, from the extinct volcano Katunga, consists of the assemblage kalsilite, melilite, olivine, perovskite and iron-ore, together with some glass. As all these minerals are unsaturated, katungite must be one of the most basic rocks possible—it contains only 34 per cent of SiO_2 . The assimilation of silica from xenoliths incorporated in the magma has led to the progressive elimination of kalsilite, the place of which is taken by leucite. At the same time the intake of additional silica causes the progressive displacement of melilite in favour of augite. Ultimately, therefore, a type was produced which consists of olivine, augite and leucite, with perovskite and iron-ore as accessories. Here we are on known ground, for this is the assemblage characteristic of olivine-leucitite. This particular variety is a melanocratic facies of the type and is termed "**ugandite**" by Holmes.²

¹ Termed "madupite" by W. Cross.

² Holmes, A., "A Suite of Volcanic Rocks from South-West Uganda . . ." *Min. Mag.*, xxvi (1942), p. 197.

In the magmatic sense ugandite is the equivalent of the deep-seated "kimberlite" of the South African volcanic pipes.

THE ORIGIN OF THE LEUCITIC LAVAS

Although leucitic lavas are of wide distribution, in bulk they are nowhere spectacular. The Roman volcanic province is the most extensive, covering approximately 2,000 square miles; while the Central African province, referred to above, occupies some 1,500 square miles. In Java leucitic lavas have been emitted from a line of volcanoes extending over 300 miles. In North America the Leucite Hills in Wyoming remain the only considerable area of leucitic rocks. Similar rocks have been most recently discovered in the West Kimberley area in Western Australia, referred to above. On account of their quantitative insignificance, it is obvious that we are not dealing with normal differentiates of one of the widespread magma-types. Probably we are dealing not with one problem of origin, but two. In the Roman province the dominant type is leucite-basanite, which in effect is olivine-basalt, with leucite in addition. There is thus strong presumptive evidence that the original magma was basaltic. In the Central African province, on the other hand, the leucitic rocks are not associated with basaltic derivatives, but with a variety of ultrabasic (peridotitic) rocks represented by blocks in the agglomerates, and xenoliths in the lavas themselves. The close association led A. Holmes to claim a genetic relationship between the leucitic lavas and a peridotitic magma. He thought that to produce ugandite from peridotite it was necessary to abstract, by crystallization, certain high-temperature and high-pressure components, notably eclogite. The abstraction of the latter, with the abnormally high soda to potash ratio of 9 to 1, would give approximately the requisite preponderance of potash over soda that characterizes the Uganda leucitic rocks. Two points arise here: firstly, there is no tangible evidence that eclogite was in fact abstracted—it is unrepresented among the erupted blocks hereabouts. Secondly, preponderance of potash is not a prerequisite condition for the crystallization of leucite. In some leucitic rocks soda actually outweighs potash in the proportion of nearly three to one. In different families of leucitic lavas the $K_2O : Na_2O$ ratio is, on average, 3.8, 3.6, 3.1, 3.0, 2.3, 2.1 and 1.6 while in individual rock-types it ranges from 0.4 in a leucitite and 0.9 in a leucite-basanite, to 9.0 and 6.7 in Leucite Hills types. This is only to be expected as there is every gradation from exclusively leucitic leucitites to exclusively nephelinic nephelinites and olivine-nephelinites. Similarly, the silica percentage varies from over 55 to 33 per cent. Summarily, the leucitic lavas cover a very wide range of chemical

composition, and it is very unlikely that they have all originated from one type of magma, and in one way. It appears to us likely that the physical control during crystallization may be more important than the actual composition of the magma. In a sense all rocks containing orthoclase—and they are many—are potentially leucite-bearing under certain conditions. In the vast majority of cases the leucite is prevented from crystallizing as the magma contains too much silica, therefore the solution seems to be to remove the surplus silica. It has been shown above that desilication is effected by the assimilation of limestone or ultrabasic material. Obviously it is only necessary to invoke desilication when the original magma is silica-rich. One stage in the process is eliminated by starting, as Holmes did, with an ultrabasic magma. Shand has argued the case for limestone assimilation: it is strongest in the case of the Roman province where the magma-source underlies a massive limestone formation; it is weakest in Uganda, where there is no obvious assimilable limestone; but one can always claim deep-seated assimilation, and this is not possible to disprove. It is important to realize that since leucite originates, and is only stable at, high temperatures, it is produced in magmas at depth, and only becomes visible at the surface when these magmas are erupted and rapidly chilled. Thus they can never be seen in actual contact with the material to which they owe their origin. In this respect they stand in marked contrast to nephelinitic rocks, whose origin is established in many cases by their field relations. With the leucitic rocks the only hope on these lines lies in the nature of the erupted blocks: and in this connection the altered limestone and lime-silicate blocks of the Roman province and the biotite-peridotite, biotite-pyroxenite and biotitite of Uganda become significant.

Much of the argument developed above is based on negative evidence. It remains to note one vital item of positive evidence. Brouwer¹ has recorded the occurrence of a small fragment of limestone surrounded by minute leucites, set in a non-leucitic matrix of normal andesite. Finally, it is intriguing to realize that by whatever process the leucitic magma was produced in Central Africa, it was so far under-silicated as to produce $KAlSiO_4$, and the microscope shows that some, at least, of the leucite resulted from silication of this kalsilite, by assimilation of siliceous xenoliths. Since describing katungite, Holmes¹ has formulated various hypotheses of origin for this suite. The original one, referred to above (p. 326) has been discarded in favour of one involving reaction between some of the components of granite, with a hypothetical carbonatite magma.

¹ Holmes, A., "Petrogenesis of katungite," *Amer. Min.*, 1950, p. 772, and *cf. Min. Mag.*, xxvi (1942), p. 214-15.

THE SYENOGABBROS AND TRACHYBASALTS

(1) SYENOGABBROS

AMONG both the basic plutonites and lavas of the same composition rocks occur in which the characters of syenites and trachytes on the one hand, and gabbros and basalts on the other, are combined. Within the general basic framework, affinity with the former should be shown by the occurrence of alkali-feldspar, while affinity with the latter should be indicated by the occurrence of plagioclase near labradorite in composition. The fundamental facts then are two in number: firstly these rocks are thoroughly basic as shown not only by their silica percentage, but also by their high colour index. Secondly, alkali- and calc-alkali feldspar occur in association, and ideally in nearly equal amounts. These facts suggest that the best group name available is syenogabbro for the coarse-grained, and trachybasalt for the fine-grained, members.

In a broad sense it might be argued that certain of the types already considered under the general heading of "alkali-rich basic igneous rocks," should fall in this category—theralite being a case in point. Be that as it may, it is agreed that true syenogabbros are not common, but that the Scottish type kentallenite is a good representative of the group.

Kentallenite¹ was discovered at Kentallen near Ballachulish in western Scotland. It is a heavy, dark-coloured rock, with prominent patches of bronzy mica and an abundance of black crystals embedded in a rather meagre feldspathic base. In thin section extensive poikilitic plates of biotite occur in intimate association with all the other components. The most abundant mineral is a light greenish augite, in euhedral crystals. Olivine is very prominent, chiefly as it is densely charged with a separation of magnetite, as a fine dust that imparts a general grey colour to the crystals, and also as irregular dendritic patches. The feldspar is not easy to deal with; but careful examination will usually show that both plagioclase and orthoclase are present, showing the same sort of relationship as in monzonite, but rather less obviously. All of these features are illustrated in Fig. 126.

¹ Hill, J. B. and Kynaston, H., "On Kentallenite and its Relation to other Rocks," *Quar. Journ. Geol. Soc.*, lvi (1900), p. 531.



FIG. 126

Kentallenite, the type-rock from Kentallen, Argyllshire, Scotland.

Olivine (close stipple) enclosing dendritic magnetite; augite (light stipple); biotite, lined; plagioclase shown in outline with traces of the twinning; orthoclase left blank; apatite also shown.

It should be realized that kentallenite is a very distinctive type of syenogabbro; but all syenogabbros are not kentallenites.

Since the original discovery, rocks resembling kentallenite have been found in the Caledonian and Old Red Sandstone complexes of the South-West Highlands at Glen Orchy and elsewhere; but not all of them are strictly to type. In some there is no orthoclase, and the extension of the definition has been advocated so as to include these rocks.¹ It seems obvious, however, that kentallenite without its orthoclase has lost its most significant feature, and is merely a biotite-olivine-melagabbro. Strangely enough kentallenite has been recorded in apparently only one foreign area: it forms part of an alkali complex on the Ishim River in western Siberia.

(II) MICROSYENOGABBRO

Rocks of medium grain size corresponding in their mineralogical attributes with syenogabbros are to be distinguished by the prefix "micro-." If and when a medium-grained rock having the special features of kentallenite comes to light, it should be named micro-kentallenite. There is no need to describe it—its characters are already well known.

(III) TRACHYBASALTS

The fine-grained equivalents of the rocks just considered are collectively known as trachybasalts, by strict analogy with the coarse-grained members of the clan. They are not easy rocks to deal with satisfactorily. There is bound to be some difficulty in differentiating between trachyandesites and trachybasalts; but the theoretical difference is obvious enough. Both are characterized by the occurrence of alkali-feldspar (of trachytic rocks) associated with plagioclase (of andesitic and basaltic rocks). The differences are the same as those between andesite and basalt: these have been already discussed (p. 257). The presence of olivine, of a plagioclase more calcic than An_{50} and a high colour index indicate trachybasalt. Normally the plagioclase occurs as phenocrysts only, but rarely some is to be found also in the groundmass. Similarly the alkali-feldspar is often restricted to the groundmass, but may occur as phenocrysts in addition. The plagioclase ranges from labradorite to anorthite; the alkali-feldspar may be any of those types appropriate to trachytic rocks—it may be sanidine, "soda-sanidine" or "anorthoclase." It frequently forms a narrow but distinct mantle around the plagioclase phenocrysts, but the greater part is microlitic. Coloured silicates

¹ Cf. Bailey, E. B., in "Geology of Glencoe and Ben Nevis," *Mem. Geol. Surv., Scotland*, 1916, p. 155.

are abundant and determine the melanocratic character of these rocks.

Several varieties have been described from the Yellowstone National Park, Wyoming, by Iddings¹ under the names **absarokites** (more basic) and **shoshonites** (less basic varieties). Washington has described lavas from Italy which are evidently on the borderline between trachyandesites and trachybasalts. Thus **vulsinite**² (Washington, 1897) contains phenocrysts of anorthite (6 per cent). There is some labradorite (12 per cent) in the groundmass; but 70 per cent of the rock is "Na-orthoclase" and the colour index is only about 10. Further, biotite occurs among the phenocrysts.

Some petrologists refer the Scottish type **mugearite** to the trachybasalts. A. Harker³ used this name for certain fine-grained rocks of basaltic appearance occurring in composite sills at Mugeary in Skye. Subsequently the same type was discovered among the Carboniferous lavas in the Midland Valley of Scotland and (although called "oligoclase-andesite" by the American petrologists who described them) in the Hawaiian volcanic province. Mugearite is thoroughly basic, and the only porphyritic coloured mineral is olivine, occurring as micro-phenocrysts. The feldspar, however, is oligoclase, forming scattered microphenocrysts and abundant fluxionally orientated microlites in the groundmass. Mugearite is certainly not a normal calc-alkaline basalt: its systematic position in the scheme of classification is debatable.

(IV) SPILITES

Still more problematical are **spilites**,⁴ the origin and significance of which have been much discussed. Spilites are basic lavas with a silica percentage little over 40; but in spite of this, the feldspar they contain is pure albite. Normally albite is found in syenitic and trachytic rocks—when it is primary. Here are grounds therefore for discussing whether or not spilite should be placed with the trachybasalts. On the grounds of its *present* mineral composition there is some support for so doing; but most spilites are strongly vesicular rocks, and the vesicles, which make up a considerable part of the rock in the aggregate, are usually calcite-filled. If, as is probably the case, the CaO in this calcite came (by leaching) from the surrounding plagioclase here is a *raison d'être* for the albite. Usually, but not always, the coloured minerals in spilites have been converted into chlorite and other secondary products. For this reason

¹ *Journ. Geol.* iii (1895), p. 935.

² *Ibid.*, v (1897), p. 35.

³ "Tertiary Igneous Rocks of Skye," *Mem. Geol. Surv.*, 1904, p. 264.

⁴ Wells, A. K., "The Problem of the Spilites," *Geol. Mag.*, 1923, p. 63; and Sandius, N., "On the Spilitic Rocks," *Geol. Mag.*, 1930, p. 1; Vuagnat, M., "Sur quelques diabases suisses: contribution à l'étude du problème des spilites et des pillow lavas," *Bull. Suisse de Min. et Pét.*, xxvi (1946), p. 155.

many petrologists dismiss spilites as merely altered basalts; but others attach significance to the mode of occurrence as well as the petrographic characters of these lavas. They are invariably submarine and usually exhibit pillow structure. The latter is so uniformly developed that some people have been misled into thinking that "spilite" and "pillow lava" are synonymous terms; this is far from being the case.

Spilites in Britain are restricted to the Precambrian and Lower Palaeozoic lavas erupted on the floor of geosynclinal seas. They are referred to in the accounts of these rocks in the last part of this book. Abroad, spilites have been described from a number of localities including the Western Altai in the U.S.S.R., and from the Anui range in north-eastern Siberia, where they are of Permo-Triassic age.

Experimental work carried out by Pentti Eskola¹ has an important bearing on the problem of the spilites and the associated "intermediate" lavas, the keratophyres, and the "acid" quartz-keratophyres. He succeeded in bringing about the albitization of basalt under laboratory conditions at temperatures as low as 250° C.

¹ Eskola, P., "An experimental illustration of the spilite reaction," *Comptes rendus Soc. Geol. Finlande*, No. 9 (1935), p. 2.

CHAPTER VII

THE ULTRAMAFITES

(I) COARSE-GRAINED: ULTRAMAFIC PLUTONITES

THE ultramafic plutonites consist essentially of ferromagnesian minerals and accessories only. The occurrence of any kind of feldspar in more than very subordinate amounts excludes a rock from this group. They never form large intrusions and never occur independently of other larger rock-bodies to which they are genetically related. This is a matter of field observation; and the field relations of these rocks are such as to demonstrate their origin by crystal accumulation. They consist of crystals of high density and early formation that were derived from a much larger body of magma by crystal sorting under the control of gravity. As a consequence of this, the ultramafites occupy the lower parts of the intrusions in which they occur, and may well be more important in the lower parts of the earth's crust than they are at high levels. Nevertheless, such rocks do occasionally occur at high levels, and this fact has led Vogt and others to visualize the possibility of remelting of crystal accumulations at low levels with the production therefore of an ultramafic magma, capable of intrusion like any other.¹ One other important consideration must be mentioned—the likelihood of derivation direct from an ultrabasic earth-shell. This is an attractive proposition which would go far towards explaining many facts concerning these rocks; but unfortunately it is not possible, in the present state of knowledge, to prove this—it remains an interesting speculation.

The ultramafites comprise several small families, which for the sake of clarity are described separately, but in fact they grade into one another.

THE PYROXENITES

For once in a while the name of this group does mean "what it says." Pyroxenites are coarse-grained, usually deep-seated rocks in which the sole essential components are pyroxenes: there is neither feldspar nor olivine in them. They may be monomineralic, or more than one kind of pyroxene may occur. According to the kind of pyroxene it is possible to distinguish **enstatite**, **hypersthene** and **bronzite**, all with orthopyroxene; and **diallagite** with clino-

¹ Niggli, P., *Gesteins- und Mineralprovinzen*, Band 1 (1923), p. 29.

pyroxene. Unfortunately "augitite" has been applied to a basic *lava* rich in augite; thus, although it is a misnomer as at present used, it is not available for the appropriate rock in this class. It goes without saying that pyroxenites are hardly ever monomineralic in the strictest sense. Of the accessories, chromite or magnetite are probably invariably present, in some rocks in considerable amount. Thus **chromite-bronzitite** occurs in the Bushveld Complex, South Africa, and grades into bronzite-chromitite in which the spinellid is far more abundant than the orthopyroxene, which occurs in large crystals poikilitically enclosing crowds of octahedra of chromite. Again, a pyroxene belonging to one group is often associated with one belonging to the other, either as discrete crystals or as lamellar intergrowths. **Augite-hypersthene** is such a rock in which the first-named mineral is accessory to the second. When dealing with rocks of such simple mineral composition it is preferable to use a compound name rather than one of the familiar place-name type. As an illustration we may note **websterite**, named by G. H. Williams from Webster, North Carolina. It contains diallage and hypersthene in unspecified proportions, and is more aptly referred to as a diallage-hypersthene-pyroxenite, while particular specimens of the rock would be more accurately named, on the lines suggested above, after measuring the proportions of the two minerals.

An important member of the group which has received considerable notice recently in connection with petrogenetic speculations is **biotite-pyroxenite**, which A. Holmes thinks may be parental to such leucitic basic lavas as the leucitites. A rock from the Newry Complex, Ireland, contains biotite 45.3, augite, 27.4, hornblende 19.4, actinolite 1.8, iron-ores 3.2, and apatite 2.9 per cent.* Similar rocks, but with varying proportions of the component minerals, occur also at Monte Somma, Uganda, Upper Burma, and elsewhere. The Newry rock might more aptly be termed pyroxene-biotitite in view of the dominance of the mica. **Biotitite** does in fact occur among the blocks in the volcanic vents in South Africa, which are such prolific sources of the ultramafic rock-types.

THE HORNBLENDITES

Once again it must regretfully be recorded that the obvious name for this group of ultramafites is preoccupied. Amphibolites are metamorphic rocks, but (one is tempted to say "of course") they do not consist solely of amphiboles, as the word implies, but are more or less of dioritic composition. Hornblendite is definitely rarer than pyroxenite, perhaps as a consequence of the lower position of

* Reynolds, D. L., "The Eastern End of the Newry Complex," *Quar. Journ. Geol. Soc.*, xc (1934), p. 585.

hornblende in the reaction series, which implies later separation and therefore less likelihood of gravitational sorting. Such examples as are known may well have originated by late-stage alteration of pyroxenites. In this connection the chemical relationship between amphiboles and pyroxenes as interpreted by Kennedy is significant, and there can be little doubt that hornblendite is the heteromorphic equivalent of two-pyroxene pyroxenite (p. 183).

Among the several kinds of ultramafites occurring at Garabal Hill¹ the main type is an augite-peridotite; but this grades into a pyroxenite consisting of augite, orthopyroxene and some brown hornblende. The latter rock in turn grades into a hornblendite (termed **davainite** by Wyllie and Scott) which is described as "a pure brown hornblende rock." It is of particularly coarse grain, with individual hornblendes up to two inches in length. The field and microscopic evidence shows that davainite has resulted from the alteration of the pyroxenite, probably through the agency of a later intrusion of gabbro.

Hornblendite is developed as a phase marginal to syenite at Kiloran on the island of Colonsay² in the Hebrides. It is essentially a coarse-grained aggregate of black hornblende crystals, and contains numbers of quartzite xenoliths surrounded regularly by reaction rims consisting of the minerals appropriate to quartz-syenite. Gradation into hornblende melasyenite is indicated by the incoming of a little micropertthitic orthoclase in some phases of the hornblendite.

THE ECLOGITES

The eclogites are of special interest and present problems of interpretation. The name is an old one, introduced in 1822 by Haüy for rocks occurring in the Fichtelgebirge, and which still remain the most typical of the eclogites. Eclogite is of notably high specific gravity; and consists of bright red garnets set in a bright green crystalline matrix. Two components are regarded as essential in eclogites—red garnet of the pyrope-almandine type, and the bright green pyroxene, omphacite. Accessories sometimes present include brilliant emerald green chrome-diopside and, strangely enough, quartz and kyanite. It has been shown by analysis that eclogite has much the same chemical composition as olivine-gabbro, but contains none of the normal gabbroic minerals: plagioclase has been completely eliminated and the other components have been broken down and redistributed. Labradorite has been split, as it were, into albite and anorthite "minerals"; the former has been desilicated into

¹ Nockolds, S. R., "The Garabal Hill-Glen Fyne Igneous Complex," *Quar. Journ. Geol. Soc.*, xcvi (1940), p. 451.

² Wright, W. B. and Bailey, E. B., "Geology of Colonsay and Oronsay," *Mem. Geol. Surv. Scotland*, 1911, pp. 28-9.

jadeite, which is incorporated in the pyroxene, omphacite. The silica released may appear as free quartz in spite of the basicity of the rock. The anorthite molecule goes into the garnet which, though fundamentally a type rich in magnesium derived from olivine and original pyroxene, does contain a certain proportion of the "lime-garnet" molecule ($\text{Ca}_2\text{Al}_2\text{Si}_2\text{O}_{12}$). The kyanite represents excess alumina and silica not required in the adjustments mentioned.¹

Typical eclogites are well represented among the blocks in the "blue ground" which fills the deeply eroded vents in the Kimberley region in South Africa. In Britain eclogites occur in northern Scotland in the so-called Lewisian inliers near Glenelg²—the first record in this country (J. J. Teall, 1891)—in central Sutherland and central Ross-shire. They there form small outcrops over a wide area, and are closely associated with injection gneisses which were originally basic igneous rocks impregnated by pegmatite. True eclogite forms only a small part of the eclogitic bands which contain cores of the typical red-garnet, omphacite rock. The latter grades into related types in which feldspar, quartz and green hornblende become important. These changes are regarded as due to retrogressive metamorphism, the ultimate product of which is garnet-amphibolite, an undoubted metamorphic rock.

The chief problem of the eclogites concerns their origin. They are believed to be products of "plutonometamorphism"—to lie on the borderline between the igneous and metamorphic. It is uncertain, however, whether they represent basic (gabbroic) igneous rocks which have been metamorphosed under extremely deep-seated conditions, or whether they represent basic *magma* which crystallized under such conditions.³ In either case, they are of outstanding interest and provide such a useful study of heteromorphism that they cannot well be omitted from a book of this kind.

It will be realized that the rocks described above, though ultramafic, are not ultrabasic—a point which is emphasized by the analysis of the Bushveld bronzitite, which though typical of its kind, has a silica percentage as high as many "intermediate" rocks (analysis I, p. 338).

THE PICRITES

The picrites were so named by Tschermak (1866) on account of their high content of magnesia (bitter-earth). The original picrites occur as intrusions in the Cretaceous and Eocene in the highlands of Moravia and Silesia. These original picrites were augite-olivine

¹ Tilley, C. E., "The Paragenesis of the Kyanite-Eclogites," *Min. Mag.*, xciv (1936), p. 422.

² Alderman, A. R., "Eclogites from the Neighbourhood of Glenelg, Inverness-shire," *Quar. Journ. Geol. Soc.*, xcii (1936), p. 488.

³ See the discussion on Dr. Alderman's paper, referred to above

rocks. Since they were described the definition has been widened to allow of the occurrence of other coloured silicates in the place of augite, and according to the current English usage, the essential feature is the presence of small amounts of plagioclase. The ferromagnesian minerals which accompany the olivine are orthopyroxene (enstatite-bronzite), augite and hornblende in different cases.

These essential components do not present any special features; but the texture is normally poikilitic, i.e., several olivines may be enclosed in a single crystal of augite, etc.

Augite-picrites occur among the Carboniferous intrusives in the Midland Valley of Scotland. Perhaps the picrite which forms part of the small island of Inchcolm in the Firth of Forth is the best known. They are associated with teschenites and evidently formed by differentiation from a teschenitic magma, or at least from the magma which gave the teschenites. The same association (of picrite with teschenite), occurs also in the type-area for the latter, Teschen in Moravia. These field relations prove these particular picrites to belong to the lineage of rock-types which includes the alkali-rich analcite-syenite, teschenite and lugarite. Augite-picrite occurs also in Argyllshire, in composite intrusions, as the lower member associated with kentallenite, notably at Glen Orchy¹ and Balnahard, Colonsay. Actually the downward succession at Glen Orchy is kentallenite – augite-picrite – hornblende-picrite – a lamprophyric phase. Thus these Caledonian augite-picrites belong to an association which is not notably alkaline.

Hornblende-picrite also is well represented in this country: it occurs among the Ordovician intrusives in North Wales, the Shelve area of Shropshire, the Caledonian intrusives in the South-West Highlands, and in a different association of rock-types in Aberdeenshire.

In Argyllshire hornblendite-picrite is associated with such calc-alkaline rocks as diorites, granodiorites and kentallenite. In the Huntley Complex² in Aberdeenshire an augite-hornblende-picrite occurs in association with olivine-gabbro, hypersthene-gabbro and troctolite.

THE PERIDOTITES

With one possible exception, discussed below, peridotites do not contain any feldspar. The only component which must be present in any rock so named is olivine, and richness in this mineral is the chief diagnostic feature of the group, as the name implies. The

¹ Kynaston, H., "Geology of the Country near Oban and Dalmally," *Mem. Geol. Surv. Scotland*, 1908, p. 92.

² Read, H. H., in "Geology of Banff, Huntly and Turriff," *Mem. Geol. Surv., Scotland*, 1923, p. 104. (Analysis VI in the appended Table.)

ANALYSES OF ULTRAMAFITES

	I. Bronzite.	II. "Biotite- pyroxenite."	III. Hornblende.	IV. Picrite.	V. Picrite.	VI. Picrite.
SiO ₂	55.40	41.71	37.90	44.73	44.47	35.72
Al ₂ O ₃	1.60	8.55	13.17	11.89	7.59	10.99
Fe ₂ O ₃	nil	2.51	8.83	4.85	6.25	3.73
FeO	9.35	9.79	8.37	6.61	10.06	6.43
MgO	32.45	14.65	9.50	10.77	11.93	26.62
CaO	0.45	11.74	10.75	7.69	10.24	3.28
Na ₂ O	tr.	0.60	2.35	2.77	4.27	0.58
K ₂ O	tr.	3.65	2.12	0.89	1.46	0.43
H ₂ O	0.15	1.57	1.40	7.64	1.21	9.30
TiO ₂	0.10	2.15	5.30	1.53	2.73	0.36
Cr ₂ O ₃	0.65	—	—	—	—	—
Other constituents .	0.45	1.82	—	1.06	0.54	2.59
	100.60	99.74	99.69	100.43	100.75	100.03

I. Bronzite, Bushveld Complex. (Anal. H. G. Weall.) A. L. Hall, *Bushveld Memoir*, 1932, p. 315.

II. Biotite-pyroxenite, Newry, Ireland. (Anal. L. S. Theobald), *Q.J.G.S.*, xc (1934), p. 585.

III. Hornblende, Brandberget, Gran, Norway—Von Schmelck, quoted from Washington's Analyses, p. 345.

IV. Picrite Sill at Blackburn, Bathgate Hills (W. Pollard).

V. Picrite, Lugar, Ayrshire (Anal. G. W. Tyrrell), *Q.J.G.S.*, lxxii (1916), p. 114.

VI. Picrite, Broadland, "Geol. of Banff, Huntly and Turriff," *Mem. Geol. Surv.*, 1923, p. 115.

olivine may be accompanied by any of the normal ferromagnesian silicates, either singly or in variety, and in consequence there are many different named peridotites, a selection of which are considered below.

Dunite (Hockstetter, 1859), is in effect an olivine-rock and is named after the original locality, Mount Dun in New Zealand. The type-rock consists of interlocking grains of olivine together with

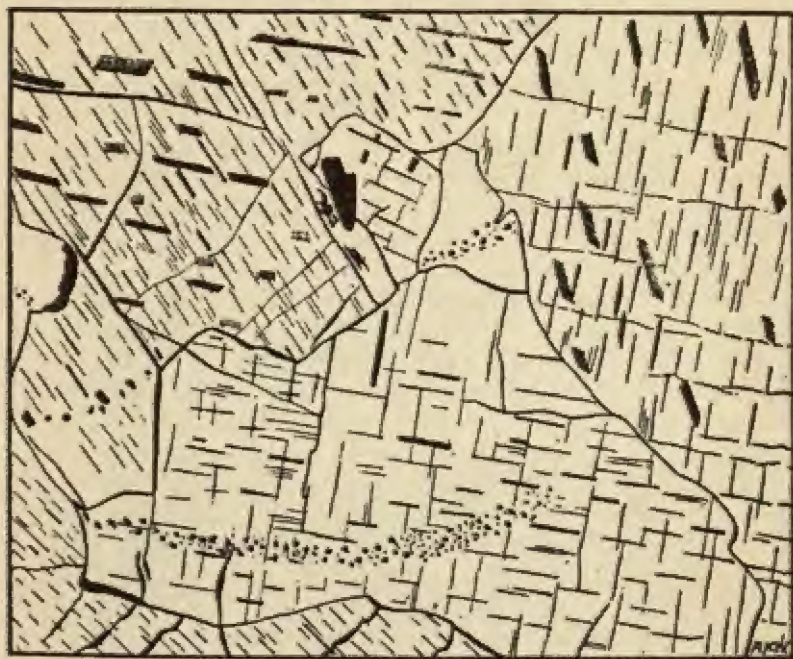


FIG. 127

Olivinite ("Hortonolite"), Mooihoek, Bushveld Complex, South Africa. Anhedronal grains of hortonolite showing cleavages and included dendritic plates of iron-ore regularly orientated in two directions.

scattered crystals of chromite. The dunites of the Bushveld Complex have been carefully studied both as regards the three-dimensional form of the intrusions and petrographic detail, as some of them have been deeply mined in the search for minerals of the platinum group which are obtained from these rocks. In shape the intrusions are inverted cones tapering downwards, and they show a cross-cutting relationship to the other members of the Complex. The "hortonolite" is distinctive among olivines as it shows good cleavages, distinct twinning, and regularly orientated inclusions of dendritic magnetite (Figs. 127 and 128).

In peridotites of this type, the olivine is normally rich in magnesium and individual rocks may consist of chrysolite or hortonolite. Thus chrysolitite and hortonolitite are specific varieties of "olivinites." In chemical composition olivinities show analyses like those of the individual minerals. With the incoming of a little alumina, this combines with MgO or FeO to give the almost constant accessory, spinel. With rather more silica, orthopyroxene appears, as in one type from the kimberlite pipes (see below). This contains relatively

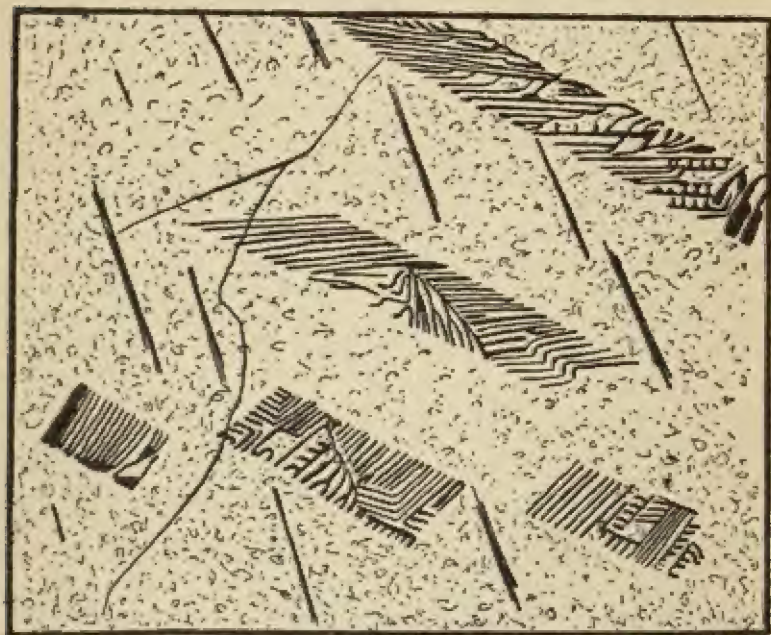


FIG. 128

A.K.W.

Regularly orientated plates of dendritic iron-ore in hortonolite. Same rock as that illustrated in Fig. 127, drawn under $\frac{1}{4}$ -inch objective.

large, somewhat rounded grains of orthopyroxene set in a matrix of granular olivine showing signs of mechanical granulation, with the usual spinel.

Apart from the olivinities the simplest peridotites consist of olivine together with mica (phlogopitic), pyroxene or hornblende. They are best named in the obvious manner as mica-peridotite, etc., although old-type names have been applied to many of these combinations: wehrlite and lherzolite are examples, but they are singularly uninformative and are best not used.

An example of one of the simpler types of peridotite forms part

of the Garabal Hill-Glen Fyne complex.¹ It is a pyroxene-peridotite with augite the most abundant mineral, enclosing olivine largely converted into serpentine, together with iron-ore and occasionally flakes of mica or hornblende. With the incoming of plagioclase in small amounts this augite-peridotite grades into augite-picrite.

The simple hornblende-olivine combination appears to be rare; but there are several types of peridotites in which hornblende is associated with other mafic minerals. Such is the so-called **scyelite**, named from Loch Scye in Sutherland by Judd (1885). In the hand-specimen this is a distinctive, heavy, dark-coloured rock with very large (1-inch) hornblende and mica crystals showing lustre-mottling. The reflection of light from the cleavage surfaces of these minerals is interrupted by black spots, seen under the microscope to be serpentine pseudomorphs after olivines. These are poikilitically enclosed in a bleached phlogopitic mica and in light-green hornblende. Minute overlapping hexagonal plates of doubtful composition cause a schiller effect in the mica. These features are illustrated in Fig. 129.

Cortlandtite is the name given to a rock in the Cortlandt Complex on the Hudson River, New York; but as Shand has recently pointed out, the rocks are exceedingly variable and it is consequently difficult and from one point of view rather pointless to attempt to define the type, when there is continuous variation in several directions.² As originally defined, cortlandtite was a hornblende-hypersthene-peridotite containing malacolite (colourless clinopyroxene) and some mica. Peridotites of this type form small bosses near the Ballachulish granite in Argyllshire.³

Kimberlite is a type of mica-peridotite, of great importance on account of its connection with the diamond-mining industry. It fills the volcanic necks which occur in the Kimberley district in South Africa; it is highly altered and contains blocks, some of large size, of a wonderful variety of ultramafites. Kimberlite has figured rather prominently in petrogenetic speculations concerning the reality of an ultrabasic magma. Holmes⁴ has drawn attention to certain distinctive features in the chemical composition of these rocks, particularly in relation to the amounts of certain rarer elements in them, and uses these facts to support his arguments for

¹ Nockolds, S. R., "The Garabal Hill-Glen Fyne Igneous Complex," *Quar. Journ. Geol. Soc.*, xcvi (1940), p. 452.

² Shand, S. J., "Phase Petrology of the Cortlandtite Complex," *Bull. Geol. Soc. Amer.*, liii (1942), p. 409.

³ Bailey, E. B., "Geology of Ben Nevis and Glencoe," *Mem. Geol. Surv.*, 1916, p. 172.

⁴ Holmes, A. and Harwood, H. F., "Petrology of the Volcanic Fields E. and S.E. of Ruwenzori, Uganda," *Quar. Journ. Geol. Soc.*, lxxxviii (1932), p. 370.

the existence of an ultrabasic earth shell, from which a peridotitic magma may be drawn. Carbonatic kimberlite occurs as dykes in the Alnö Complex, Sweden.

An ultrabasic complex of Tertiary age has been described by Harker, from the island of Rum in the Hebrides. It consists in general terms of alternating sheets of peridotite and allivalite (p. 290). In detail these two members show a considerable amount of variation:



FIG. 129

Scyelite, Loch Scye, Sutherland.

Upper part of the field occupied by basal and vertical sections of nearly colourless amphibole; the lower part, by phlogopitic mica. Serpentine pseudomorphs enclosed poikilitically in other minerals. Magnetite in octahedra. Hexagonal plates, seen end-on, causing schiller structure in the mica.

within the allivalite sheets all gradations may be found between anorthosite and olivinite. Essentially the same kind of variation has been noted in the layered complex at Belhelvie, which in the wide sense is troctolite, but which again varies between pure olivinite and pure anorthite-rock. Now a drastic change in chemical composition is necessary to bring plagioclase into olivinite: and in

so doing an important phase boundary is crossed. There can be no latitude so far as plagioclase is concerned—there is none in olivinite. But in allivalite both olivine and anorthite are *essential* constituents. Therefore between olivinite and allivalite lies the connecting link consisting of dominant olivine, with accessory *anorthite*. There is no convenient name for this type. It is far removed from picrite. If "peridotite" implied a rock-type in which olivine is dominant, regardless of its minor constituents, this rock could be aptly termed **anorthite-peridotite**: indeed, at present, there is no alternative, though acceptance of the term destroys the definition of peridotite as being feldspar-free.

THE SERPENTINITES

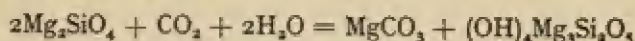
Although as a rule special names are not recognized for altered rocks belonging to named types, serpentinite is an exception. These rocks consist essentially of the mineral serpentine, and are popularly themselves called "serpentine." It is awkward, however, to use a word with two meanings, and hence we adopt "serpentinite" as the rock name, retaining "serpentine" for the mineral.

Serpentinites are compact, variously coloured rocks, often banded, blotched and streaked with bright green and red, the general body of the rock being any colour between light greyish-green and greenish-black. On account of their attractive colouring and because they can be shaped and polished easily, they are used for ornamental purposes.

In some specimens relics of original minerals may remain and give an indication of the nature of the unaltered rock. From such evidence it has been proved that ultramafites and less commonly ordinary basic rocks such as gabbros can be changed into serpentinites. As is well known from the familiar pseudomorphs after olivine, the serpentine is often formed in such a manner as to retain sufficient of the character of the original mineral (although no actual fragment of the latter may have survived replacement), as to make its identification easy. Although ultramafites often show the effects of weathering by the development of superficial serpentine, in serpentinites the alteration goes so deep, and is so generally developed, that it cannot be attributed to mere weathering. It recalls the wholesale kaolinization of certain granites, and there is little doubt that serpentinization on this scale arises from a similar cause. W. N. Benson¹ has developed the hypothesis that the process is essentially one of autometamorphism—the agent of alteration being magmatic—not meteoric—water. In many instances veins of talc and mag-

¹ *Amer. Journ. Sci.*, xlv (1918), p. 693; but cf. Bowen and Tuttle, O. F., "The System MgO—SiO₂—H₂O," *Bull. Geol. Soc. Amer.*, lx (1949), p. 439.

nesite are developed on an extensive scale. In the latter case the action of CO_2 is indicated:—



In Britain serpentinites are not widely distributed. The best known occurrences are found in the Lizard Complex in South Cornwall, Anglesey in North Wales, and Portsoy in Banffshire, Scotland.

ANALYSES OF PERIDOTITES

	I. Dunite.	II. Hortonolite- Dunite.	III. Mica- Peridotite (Basaltic Kimberlite).	IV. Kimberlite (Ordinary).	V. Scyelite.
SiO_2 . .	42.8	34.38	30.66	37.77	43.56
Al_2O_3 . .	—	1.46	2.86	3.00	3.06
Fe_2O_3 . .	—	0.03	3.08	6.75	3.59
FeO . .	9.4	38.30	5.98	2.73	3.80
MgO . .	47.4	22.09	31.24	30.53	31.32
CaO . .	—	2.36	10.92	3.00	3.57
Na_2O . .	—	0.20	0.17	0.32	1.31
K_2O . .	—	—	1.23	1.28	0.29
H_2O . .	0.6	0.55	3.94	10.90	8.18
TiO_2 . .	—	0.05	1.63	1.54	0.37
CO_2 . .	—	tr.	6.00	1.30	1.31
Cr_2O_3 . .	—	0.10	—	—	—
Other components	—	0.45	2.35	0.88	0.80
	100.2	99.97	100.06	100.00	100.16

I. Dunite, Dun Mountains, New Zealand (Reuter).

II. Hortonolite-dunite, Onverwacht, Bushveld Complex. (Anal. H. G. Weall), A. L. Hall, "Bushveld Memoir," 1932, p. 325.

III. Kimberlite (Basaltic) Dutoitspan, Kimberley. (Anal. L. S. Theobald), A. Holmes and H. F. Harwood, *Q.J.G.S.*, lxxxviii (1932), p. 421.

IV. Kimberlite, average of six ordinary types. R. A. Daly, 1933, p. 552.

V. Scyelite, Central Sutherland. (Anal. B. E. Dixon), *Mem. Geol. Surv.*, 1931, p. 168.

(II) THE FINE-GRAINED ULTRAMAFITES

In the early classifications an attempt was made to accommodate certain lavas which are outstandingly rich in ferromagnesian silicates

by erecting a special category of "magma-basalts." It is difficult to understand how such a name came to be chosen, and there is no good reason for continuing to use it: the term here used as a heading is self-explanatory, though it must be admitted that the category is not easily defined in precise terms. The original "magma-basalts" included limburgite and augite. Both have clinopyroxene as the chief material; but while limburgite is rich in olivine, the latter is absent from augite. The melilite-bearing lavas (with certain coarse-grained equivalents) must also be included.

Limburgite (Rosenbusch, 1872) contains numbers of euhedral olivine phenocrysts and much titanite, which, together with magnetite and accessories, are embedded in a glassy base. Ideally there is no feldspar either as phenocrysts or in the groundmass. Thus, apart from the non-crystalline material, the mineral composition is much like that of an augite-peridotite. The non-crystalline material is significant, however. Re-examination of the type-rock has shown that only one phase of the mass is feldspar-free: other phases do contain basic plagioclase, which strongly suggests that the glass in the feldspar-free limburgite has the composition of, say, bytownite. This puts limburgite in its correct setting, as an ultramafic basalt, containing accessory, or occult basic plagioclase. It will be remembered that certain basalts (oceanites), are notably rich in phenocrystic olivine, and correspondingly poor in feldspar. Limburgite has moved farther along this line of variation.

The second type, **augite**, is probably as near to being a monomineralic lava as any rock, so far as the crystalline portion of the rock is concerned. Titanites, displaying at their best such characters as zoning, hour-glass structure, simple and lamellar twinning and strong dispersion, make this a very attractive object in thin section. The groundmass is non-crystalline, very dense and highly charged with iron-ore. The nature of the non-crystalline groundmass remains unknown. Ignoring the groundmass, the mineralogical similarity to pyroxenite is obvious; but it would be rash to suggest any genetic link on that evidence.

Among the finer-grained ultrabasic rocks melilite is found both in lavas and in dykes of lamprophyric type. The melilite-bearing lavas bear a superficial resemblance to some basalts, and are usually classified as "**melilite-basalts**"; but few, if any, have the mineral composition that is implied by that term. The original "melilite-basalt" was described from Hochbohl in the Swabian Alps as long ago as 1883. Its ultrabasic character is shown by its extremely low silica percentage (only 34 per cent), and by its mineral composition: nearly half the rock consists of olivine, 37 per cent is melilite, while small quantities of nepheline, apatite, perovskite and calcite also

occur. This type, by analogy with the feldspathoidal lavas, must be termed (with some regret, as it is an obvious misnomer), "olivine-melilitite." A nepheline-olivine-melilitite, in which nepheline becomes an essential, not merely an accessory component, has been described from Tasmania.

Other olivine-melilitites, differing from the original one only in points of detail, occur at several localities in South Africa, notably in Namaqualand. Not all of these are lavas: some are intrusive.

Although the rock called **alnöite**, from Alnö, an island off the coast of Sweden, was originally classed as melilite-basalt, the name was changed by Rosenbusch to alnöite, *on the grounds that it is intrusive*. Although we strongly disagree with Rosenbusch's reason for changing the name, alnöite is sufficiently distinctive in itself to justify its name. Fundamentally the type is one-third each of melilite and biotite, the remainder of the rock being made up of pyroxene, calcite and olivine in order of importance, with various minor accessories. At Isle Cadieux¹ between Montreal and Ottawa, a small intrusive complex of alnöitic rocks occurs. Two types in particular are outstanding: one contains the mineral monticellite in addition to ordinary olivine (chrysolite); while the other, occurring as mere streaks in the alnöite, consists almost wholly of biotite and melilite.

A new occurrence of melilite-bearing rocks has recently been recorded by A. Holmes from the volcanic province of South-West Uganda. The volcanic rocks here include types of outstanding interest, as they contain the potassic analogue of nepheline, **kalsilite**. Among these types collectively known as the Mafurite series, is **ugandite**, a fine-grained assemblage of olivine, augite and leucite as essential components, and perovskite and iron-ore as common accessories. In other types, more completely under-saturated, **kalsilite** takes the place of leucite, while in the most basic, **kalsilite** occurs in association with melilite. Holmes terms this rock **kalsilite-katungite**.²

Two types of melilite-bearing rocks of coarse grain have been described:—

Turjaite, so named by Ramsay in 1921, forms a small intrusion at Turja in the Kola Peninsula. In hand-specimens large crystals of titaniferous biotite are conspicuous, set in a matrix of melilite,

¹ Bowen, N. L., "Genetic Features of Alnöitic Rocks at Isle Cadieux, Quebec, *Amer. Journ. Sci.*, iii (1922), p. 1.

² Holmes, A., "Kalsilite-bearing Lavas of . . . S.W. Uganda," *Trans. Roy. Soc., Edin.*, lxi (1945), p. 359.

Holmes, A., *Min. Mag.*, xxvi (1942), p. 197.

which makes up nearly half the rock. Nepheline, too, is an essential component, while apatite (very abundant in some facies of the rock, magnetite, and as might be expected, perovskite, are important accessories. Although olivine and melanite garnet are usually rare, they also become important in some specimens. The frequent occurrence of calcite, as in certain nepheline-syenites, and the association of melilite-bearing rocks with carbonatites are significant facts bearing on the genesis of this rock.

Of still more extraordinary composition is the rock, also judged from its grain-size to be deep-seated, termed *Okaite* by Stansfield.¹ In its mineral composition okaite is very close to turjaite, but melilite is slightly more abundant, biotite less so, while the place of nepheline is taken by hauyne. The type-rock was discovered in the Oka Hills, near Quebec, and although a great rarity, it is noteworthy as having a particularly low silica percentage, only 29, while it contains 25 per cent of lime (CaO).

As regards origin, the following facts seem significant:—

(1) The close association of many, but not all, melilite-bearing rocks with limestones, including "carbonatites"; and the occurrence of grains of so-called "primary calcite" in many of them.

(2) The silica-percentage is the lowest, and the lime-content the highest in igneous rocks.

(3) At high temperatures nepheline and augite combine to form olivine and melilite (with monticellite as an intermediate product of the reaction).

(4) When calcium carbonate is added to fused dolerite (*i.e.*, basaltic magma), melilite crystallizes from the melt.

(5) Melilite occurs in the reaction zone between dolerite and chalk, at Scawt Hill, Co. Antrim (p. 101).

These facts strongly suggest that desilication of basaltic magma by the assimilation of calcium carbonate is one way in which melilite-bearing rocks may originate, and probably the only way.

Finally, if "ultramafic" is interpreted in the relative sense, as implying richness in mafic minerals relative to the parent magma, or associated rock-types, then lamprophyres must also be grouped under this heading. Many lamprophyres are associated with granite, and relative to granite are ultramafic differentiates, though they are far removed from being ultrabasic, like limburgite, augitite and olivine-melilitite. For this reason they are treated separately.

¹ *Geol. Mag.*, ix (1923), p. 440.

ANALYSES OF OLIVINE-MELILITITE, LIMBURGITE AND AUGITITE

	I. Olivine- melilitite.	II. Limburgite.	III. Limburgite.	IV. Augitite.
SiO ₂	35.72	42.78	40.2	41.05
Al ₂ O ₃	9.56	8.66	12.8	24.19
Fe ₂ O ₃	5.41	—	4.0	9.51
FeO	6.55	17.96	10.4	—
MgO	15.46	10.06	11.9	5.11
CaO	14.20	12.29	10.4	10.99
Na ₂ O	3.35	2.31	2.7	5.69
K ₂ O	1.67	0.62	0.8	1.89
H ₂ O	4.78	3.96	3.4	1.62
TiO ₂	2.67	0.28	2.9	—
Other constituents	0.63	0.95	—	—
	100.00	99.87	99.5	100.05

I. Olivine-melilitite, average of five analyses, R. A. Daly, 1933, p. 25.

II. Limburgite, Limburg, Kaiserstuhl, Baden (quoted from Rosenbusch's *Elemente der Gesteinslehre*).

III. Limburgite, Whitelaw Hill, Garlton Hills, Haddingtonshire (J. H. Player).

IV. Augitite, Madeiral, São Vicente, Cape Verde Islands (Doelter).

THE LAMPROPHYRES

In any scheme of classification it is difficult to fit in the curious rocks grouped under this heading, for some are associated in the field, and are therefore genetically linked, with each of the major rock-groups dealt with in the previous pages. Specific types might therefore have been dealt with under the headings granitic, syenitic, dioritic or gabbroic rocks; but something is to be gained by considering them together as one group. As rock specimens, most are unconvincing: they may closely resemble normal igneous rocks in the medium and fine grain-size groups, and from the examination of hand-specimens alone would almost inevitably be misidentified. Identification is possible only after examination of the field relations and microscopic characters.

The lamprophyres were so named by von Gümbel (1887) when describing the "mica-traps" of the Fichtelgebirge, and had reference to the lustrous character of some types due to the presence of abundant phenocrysts of biotite. The term lamprophyre is now

applied to a group of melanocratic dyke rocks irrespective of the nature of the ferromagnesian minerals of which they largely consist.

Speaking generally the lamprophyres are strongly porphyritic with abundant phenocrysts of any of the following: dark mica, augite, hornblende and olivine. These are set in a groundmass of alkali-feldspar normally, though in one group it is plagioclase near andesine in composition, while another group comprises the feldspar-free lamprophyres.

Undoubtedly the most striking phenocrysts occur in the mica-bearing lamprophyres: the abundance and large size of the biotite crystals causes a very distinctive appearance in the hand-specimen, while under the microscope the perfect idiomorphism of the mica is unique. In common with all the other mafic constituents, the biotite may be corroded to almost any degree; while internal bleaching with the development of a complementary dark margin is a constant feature. Less commonly they may display a striking colour zoning (Fig. 130).

The amphibole in lamprophyres is of two very different types: it is a green common hornblende in lamprophyres of dioritic affinities; but is a sodic variety, often barkevikite, in those associated with sodic syenites such as foyaite.

Similarly a light-greenish diopsidic augite is commonly seen in association with biotite in lamprophyres associated with granites and diorites; but titanite is often abundant in lamprophyre-dykes of foyaite affinities. In the rock illustrated in Fig. 130 the pyroxene is zoned, a greenish core being surrounded by a colourless outer zone, while the margins are slightly granulated and in places surrounded by a reaction rim of granular bright green hornblende.

Lamprophyres of all types are liable to contain pseudomorphs after olivine, as isolated euhedral crystals, or as synneusis aggregates. A particularly striking feature of many lamprophyres is the close association of perfectly unaltered biotite with completely pseudomorphed olivines. Although serpentine may occur in these pseudomorphs, very frequently the latter consist chiefly of carbonate. Although sometimes identified as calcite, it is reasonable to expect this carbonate to be magnesite, ankerite or at least dolomite. The carbonate is by no means restricted to the olivine pseudomorphs, however; it is often so abundant in the body of the rock as to cause effervescence with dilute acid. In even the freshest lamprophyres the olivine is consistently pseudomorphed; but actually these rocks are, in many instances, highly altered. In extreme cases they consist almost entirely of secondary minerals such as chlorite, carbonates, quartz, chalcedony and limonite. It is difficult to decide to what extent this is due to weathering; but there is little doubt that

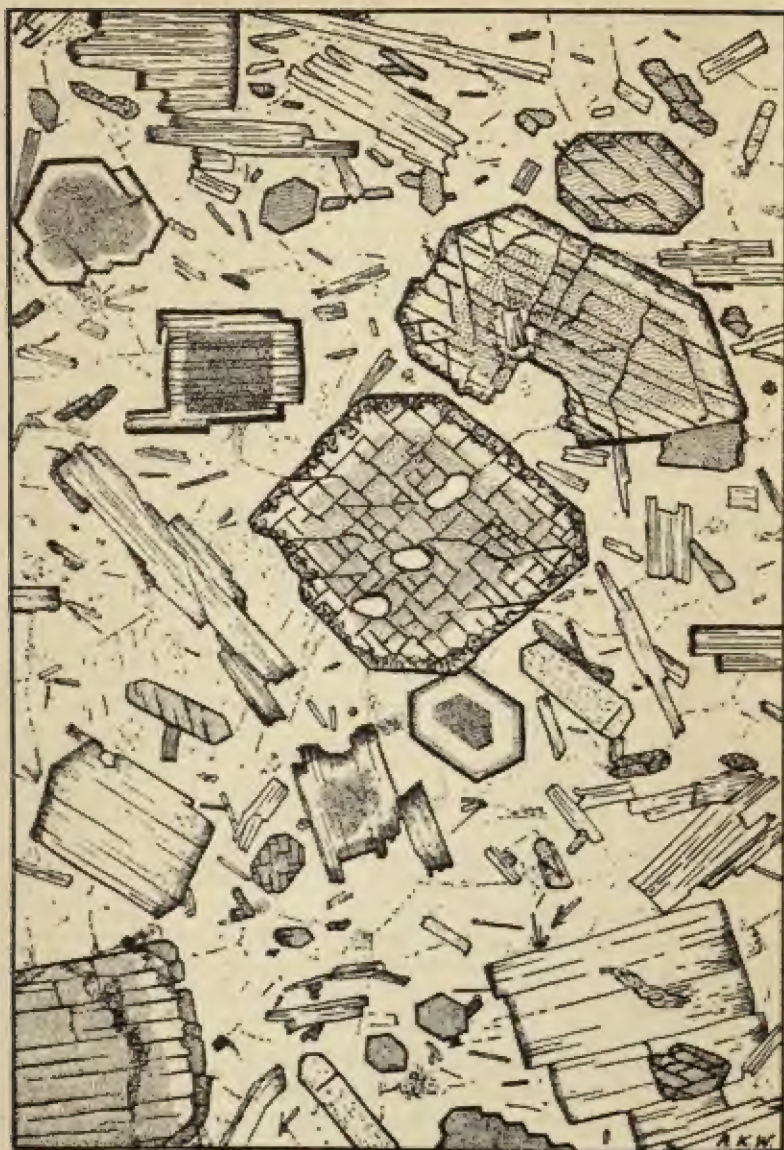


FIG. 130

Augite-minette, South Hill, St. Helier, Jersey.

Phenocrysts of diopside pyroxene subordinate to biotite, some crystals of which are beautifully zoned. Hornblende rare. The chief accessory is apatite in two generations: large euhedral phenocrysts and minute needles. Orthoclase forms the matrix in which all the other components are embedded.

it is largely a late-stage, autometamorphic effect, due to a residual concentration of magmatic water, carbon-dioxide, etc.

The mafic minerals described above are liable to occur as a second generation in the groundmass, associated in the commoner types with abundant alkali-feldspar, and, in the feldspar-free group, with analcite. Occasionally the feldspar is quite fresh, water-clear in thin section, and poikilitic towards the other components. More commonly it is microlitic and may be much altered. Rarely the groundmass consists of light-brown glass which devitrification converts into fibrous subspherulitic aggregates of orthoclase microlites. Minute octahedrons of magnetite may be plentifully scattered throughout, while a high content of apatite, varying from stout prisms to delicate needles, is characteristic.

Classification and Nomenclature.

Since in so many lamprophyres it is difficult or impossible to identify the feldspar accurately, while on the other hand the most striking and most easily identified components are the mafic minerals, the most useful general classification is based on the latter, thus:—

mica-lamprophyre, hornblende-lamprophyre, augite-lamprophyre.

But when the rock is sufficiently well-preserved to allow identification of the groundmass minerals, each of these main categories may be subdivided in the manner suggested by Rosenbusch, as shown in the table on page 352.

The advantage of Rosenbusch's classification lies in the fact that the relationship between a lamprophyre and the parental magma from which it was derived is indicated. Thus the types with dominant orthoclase—minette and vogesite (Fig. 131)—are associated with granites; the plagioclase-bearing types, kersantite and spessartite, are allied to diorites, and are often associated in the field with diorite-porphyrries and microdiorites. Finally, camptonite and monchiquite are associated with highly alkaline deep-seated rocks such as foyaite and other sodic syenites.

Chemical Characteristics and Petrogenesis.

The chemical characteristics of lamprophyres are shown in the table on page 353. It will be noted that, although they contain less alkali than the aplites, in proportion to their silica percentage they are rich in alkalis, while the CaO is very high. In the mica-lamprophyres a proportion of the K_2O goes to form biotite, and in consequence of the high content of this very basic silicate, such rocks with a silica percentage of under 50 may contain a good deal of free quartz.

The presence of much CO_2 and water is characteristic, and in this and other respects lamprophyres stand in contrast to aplites, with which they may be closely associated in the field, and to which they are said to be complementary.

The strongly corroded and highly altered state of the phenocrysts in many lamprophyres proves the former to have been "out of sympathy with their environment," and this fact is interpreted as implying different origins for phenocrysts and groundmass.

TABLE SHOWING ESSENTIAL MINERAL COMPOSITION OF
SOME TYPES OF LAMPROPHYRES

	<i>With Orthoclase</i>	<i>With Plagioclase</i>	<i>No Feldspar</i>
Biotite	MINETTE (if with augite, augite-minette)	KERSANTITE (if with augite, augite-kersan- tite)	ALNÖITE (with melilite)
Common Hornblende	VOGESITE	SPESSARTITE MALCHITE (= aphyric Spessartite)	
Barkevikite and/or Augite		CAMPTONITE (barkevikite in type-rock from Campton Falls, New Hampshire)	MONCHIQUEITE (with analcite)

Bowen regards the phenocrysts as crystal accumulations, and stresses the alkali-rich nature of the matrix in which they are embedded. Tidmarsh in describing some of the Exeter lavas, which show many of the characters of lamprophyres, invoked mixing and interaction between two residua: the one, a "depth residuum," which would be highly charged with crystals of mafic minerals; the other, an alkaline residuum, such as might, in the pure state, have crystallized as aplite.

Thus lamprophyres are abnormal rocks: they represent a small highly-specialized magma-fraction, and must be carefully distinguished from dyke-rocks which have originated in other, more

AVERAGE ANALYSES OF SOME TYPES OF LAMPROPHYRE.

	I. Minette (Osann, Clarke).	II. Kernanite (Osann, Rosenbusch).	III. Vogelste (Osann).	IV. Camptonite (Osann).	V. Monchiquite (Osann).	VI. Alnöite, Alnö, Sweden (Osann).
No. of Analyses	10	20	4	15	16	
SiO ₂	49.45	50.79	52.62	40.70	45.17	24.19
Al ₂ O ₃	14.41	15.26	14.86	16.02	14.78	12.00
Fe ₂ O ₃	3.39	3.29	3.60	5.43	5.10	6.45
FeO	5.01	5.54	4.18	7.84	5.05	9.32
MgO	8.26	6.33	8.55	5.43	6.26	14.07
CaO	6.73	5.73	5.86	9.36	11.06	17.37
Na ₂ O	2.54	3.12	3.21	3.23	3.69	1.99
K ₂ O	4.69	2.79	2.83	1.76	2.73	3.06
H ₂ O	2.43	3.10	2.70	2.62	3.40	5.16
TiO ₂	1.23	1.02	0.54	3.86	1.90	—
Co ₂	0.61	2.61	—	2.97	—	2.77
Other constituents	1.25	0.42	1.05	0.78	0.86	3.96
	100.00	100.00	100.00	100.00	100.00	100.34

normal ways. There is a modern tendency, much to be deplored, to use the term "lamprophyric" as an adjective to describe any relatively melanocratic facies of syenitic or dioritic dyke-rocks. Thus



FIG. 131

Vogesite, Ards Peninsula, Ireland.

Common hornblende, stippled; magnetite in small octahedra; small areas of quartz, the largest with a rim of small hornblendes. Orthoclase chiefly in small lath-shaped crystals. Rhombohedral carbonate, *top, left*.

hornblende in association with an "intermediate" plagioclase constitutes the normal assemblage to be expected in dyke-rocks derived from a dioritic source. Just as the parental rock-types vary widely in the proportion of light to dark constituents, so their dyke-equiva-

lents must be expected to show similar variation. Some will be melanocratic, but lack the other attributes of true lamprophyres, the corroded phenocrysts and evidence of interaction between accumulated crystals and an alkali residuum. They are in fact merely melanocratic microdiorites.

The lamprophyres which agree most closely with the postulated conditions of formation are the mica-lamprophyres. Their complementary relationship to aplites, and the ultimate derivation of both from granitic magma, are proved by their field relations.¹ The lack of harmony between the mafic phenocrysts and the material of the groundmass is proved by evidence of the thin sections.

In the (so-called) feldspar-free lamprophyres the **monchiquites** are outstanding. The name has reference to the Caldas de Monchique in Portugal, whence the original monchiquites were described by Rosenbusch (1890). These rocks are compact and black in hand-specimens, and superficially resemble basalts, but often contain very large phenocrysts (or xenocrysts) of bronzy biotite. Ideally they contain no feldspar, but otherwise resemble other types of lamprophyre, though probably they are even richer in dark minerals. The latter may be olivine, augite, often titaniferous, amphibole or biotite. These minerals are embedded in an isotropic base, which in some cases has been identified as analcite, though in others it appears to be glass and may have the composition of melilite. In the original monchiquite the base has lately been shown to have the composition of a mixture of basic plagioclase and nepheline. Obviously the mere presence of an isotropic base cannot be considered the diagnostic feature of a rock-type, and re-examination of this group seems necessary. If the suppressed phase had been allowed to crystallize, the true affinities of the rock would have been clear. If, for example, it was plagioclase, then the appropriate name to apply would be *camptonite*: the term *monchiquite* should be restricted to basic lamprophyres with an analcitic base. These rocks frequently contain analcite in a more obvious form—as small circular areas resembling vesicles, but termed *ocelli*.

Monchiquites are not common rocks in Britain. Interesting examples have been described from the Orkney Islands,² and include a biotite-monchiquite containing many phenocrysts of olivine associated with large biotites. Augite occurs as smaller crystals making up a large part of the groundmass, while the base has been decomposed to a mixture of calcite and fibrous zeolites: its original nature remains unknown. A monchiquite dyke is intrusive into the

¹ Cf. Smith, H. G., "New Lamprophyres and Monchiquites from Jersey," *Quar. Journ. Geol. Soc.*, xcii (1936), p. 379 (at foot of page).

² Flett, J. S., *Trans. Roy. Soc. Edin.*, xix (1900), p. 887.

Old Red Sandstone of Monmouthshire.¹ As is so often the case, this lamprophyre contains many corroded xenocrysts, including augite crystals up to 6 inches in length, plates of biotite 2 inches across and grains of quartz. The groundmass is analcitic, so the rock is a true monchiquite.

The **alnöites** are sometimes regarded as a type of feldspar-free, biotite-rich lamprophyre, allied to monchiquite. The type has already been referred to, as it contains melilite and perovskite.

Examples of the feldspar-bearing lamprophyres are widespread in Britain, and a comprehensive list would occupy much space. A few typical occurrences are noted, to serve as illustrations only. The North Country lamprophyres occur as narrow dykes over an area extending from Teesdale to Furness, and from Bassenthwaite to Ingleton—a circular area with a diameter of 50 miles, centred about Shap Fell. On account of their radial disposition about the Shap granite, these lamprophyres are considered to be genetically related to it. The types represented are minettes and kersantites, though the distinction is not easily made on account of alteration of the groundmass. Mica-lamprophyres are well represented among the latest minor intrusions in the island of Jersey,² and are noteworthy on account of the ideally fresh condition of some of them. The example illustrated in Fig. 130 is one of the most attractive. Most of the Jersey lamprophyres are narrow vertical dykes of minette, but one or two have been identified as camptonite and monchiquites, though in the latter case, the diagnostic analcite does not seem to have been observed.

As might be expected the dyke phases connected with the Caledonian complexes of southern Scotland include hornblendic types—vogesites and spessartites. A typical example of the former is illustrated in Fig. 131, from the Ards dyke-swarm, in North-East Ireland. This rock shows a tendency for both chief minerals to be euhedral—the “pan-idiomorphic texture.” The corroded quartz xenocryst surrounded by small prisms of hornblende (bottom right-hand corner) is characteristic.

¹ Boulton, W. S., “On a Monchiquite Intrusion in the Old Red Sandstone of Monmouthshire,” *Quar. Journ. Geol. Soc.*, lxvii (1911), p. 460.

² Smith, H. G., “New Lamprophyres and Monchiquites from Jersey,” *Quar. Journ. Geol. Soc.*, xcii (1936), p. 365.

CHAPTER VIII

THE PYROCLASTIC ROCKS

THE word *pyroclastic* is applied to fragmentary rocks of volcanic origin. The fragmentary material owes its origin to volcanic explosions, and the ejectamenta are of the most varied character: thus they may consist of bombs of lava, the shape of which indicates that they were thrown out in the plastic condition; of cinders torn from lava already consolidated in the vent; or of lava-coated fragments of the sedimentary or other strata broken through during the eruption. In regard to size, the material may be composed of the finest dust (*ash*), of medium-sized fragments (*lapilli*), of *bombs*, of quite large *blocks*, or of these mixed in any proportion. Pyroclastic accumulations in which there are large blocks are known as **agglomerates**, and are usually found either actually in the vent itself or not far removed from it. Rocks composed of smaller fragments are termed **volcanic breccias**, while the finest material forms **tuffs** and **ash beds**: a distinction between the two latter terms being sometimes made to emphasize the consolidated or cemented character of the tuffs as compared with the more loosely compacted ashes.

A considerable proportion of the fine dust or ash blown out from the vent consists of glass, which at the moment of explosion was in the liquid form (*lava-spray*). It appears as elongated and tubular bodies, produced by the drawing out of steam cavities, or as fragments possessing curved or concave surfaces¹ due to the fracture of vesicular material. The remainder consists of crystals (chiefly of feldspar and various pyroxenes, and to a lesser extent of biotite, hornblende, magnetite and apatite), which were already formed and floating in the magma before its final eruption. Many of these crystals present a perfect form; but some are, of course, broken, and there is usually more or less adherent glass. When, however, the glass is very fluid at the moment of eruption, it is wiped off the surface of the crystals by friction during their rapid passage through the atmosphere.²

The composition of an ash varies with its distance from the focus of eruption: the coarsest and heaviest portion is deposited first,

¹ The *Aschenstruktur* or *Bogenstruktur* of the Germans, and the *Vitroclastic texture* of Pirsson.

² Flett, J. S., "Note on an Ash that fell on Barbados after the Eruption of St. Vincent," *Quar. Journ. Geol. Soc.*, lviii (1908), p. 369.

while the finest and lightest material may be carried by air currents to enormous distances.¹ Complex rocks are produced by the showering down of such volcanic dust into the sea, where it becomes mixed with epiclastic material and thus forms ashy limestones or ashy shales, as the case may be. In the case of pumice, the material at first floats, and may be transported by currents for long distances (as in the great eruption of Krakatoa) before it becomes water-logged and sinks to the bottom. Disintegrated pumice is an important constituent of some abyssal deposits.

Although the material composing the tuffs may be entirely of volcanic origin, in some cases it is evident from the rolled condition of the fragments that they have been transported since their first deposition (*redeposited ash*). When, as is frequently the case, a volcanic eruption is accompanied by a heavy fall of rain, the ash may fall in the form of mud, or that already deposited may be swept away as mud-flows to lower-lying land, or even into the sea. There is no doubt that many tuffs have originated in this manner; and well-known examples are the *trass* of the Brohl valley, in the Eifel district, and the *peperino lufaceo* of the Ciminian Mountains, near Rome.

Volcanic ashes undergo considerable changes after their first deposition: thus they become cemented by mineral matter (quartz, opal, chalcedony, calcite, iron-oxides, etc.) deposited from the ground-water circulating through them, and in this way hard, compact, siliceous, calcareous or ferruginous rocks are produced. The hard flinty rocks produced by the silicification of tuffs are sometimes described as *hållefinta* or *porcellanite*, according as their fracture is conchoidal or splintery. Owing to their porous nature, ash beds are particularly liable to decomposition by weathering. Sericite, quartz and calcite are developed from the feldspars, and chlorite from the pyroxenes; while the glass becomes devitrified, the most basic type giving rise by hydration to the green substance known as *palagonite*, as in the palagonite-tuffs of Sicily, Iceland, the Canary Islands and Patagonia.²

The classification of the pyroclastic rocks presents great difficulties, and at least three different criteria may be considered, viz., the size of the constituents, their lithological character and their chemical composition.³ In addition to the division according to the

¹ Judd, "On the Volcanic Phenomena of the Eruption of Krakatoa"; and "On the Nature and Distribution of the Ejected Materials." *Report of the Royal Society Commission*, London, 1889.

² Penck, "Ueber Palagonit und Basalt-tuff," *Zeitsch. d. Deutsch. Geol. Gesellsch.*, vol. xxxi (1879), pp. 504-77. See also Murray and Renard, *Challenger Reports, Deep Sea Deposits*, vol. xviii, 1891, pp. 304-11.

³ Williams, H., "Notes on the Characters and Classification of Pyroclastic Rocks," *Proc. Liverpool Geol. Soc.*, xiv (1926), p. 223.

size of the component fragments already referred to, it is also usual to style the acid, intermediate, and basic types *rhyolite-tuff*, *andesite-tuff* and *basalt-tuff*. Owing, however, to secondary silicification, ashes originally, for instance, of andesitic composition may be found to show a percentage of silica, which, on this basis alone, would cause them to be referred to the rhyolites; but the character of the feldspars and the nature of the lapilli usually furnish sufficient data for the reference of the tuffs to their proper position. In a useful study for students Pirsson¹ has divided the pyroclasts into:

- (a) Vitric tuffs,
- (b) Lithic tuffs, and
- (c) Crystal tuffs.

In the first case the components are essentially glass fragments, and are distinguished under the microscope by the vitroclastic texture. In the second case the tuff consists of stony fragments, which are more completely crystalline. In the last category, the rocks consist essentially of crystals or broken fragments of crystals.

The pyroclastic rocks play an important rôle in the history of volcanic action in Great Britain and are referred to in the last part of this book.

Fine examples of agglomerates are found filling the volcanic necks exposed on the coast of Fife; the best known are the Rock and Spindle near St. Andrews, Largo Law, and those on the strip of coast to the immediate east and west of Elie.² These agglomerates are composed of fragments of various basic lavas and of the sedimentary rocks broken through by the vents. The larger fragments are embedded in a groundmass of fine material composed largely of comminuted lava and pumice, together with broken crystals of feldspar, augite, hornblende, biotite and garnet. Some of these agglomerates have yielded fossil remains of contemporaneous plants in a state of perfect preservation. This material has proved invaluable in the study of the minute structures of the Carboniferous flora.

J. F. N. Green has shown from a study of the Lake District volcanic rocks that lavas may closely resemble true agglomerates as a consequence of autobrecciation, whereby portions of the first consolidated crust of a lava flow are incorporated in the still fluid portion. Weathering emphasizes the fragmental nature of such lava flows, and it is sometimes impossible to differentiate between them and true pyroclasts in the field, though theoretically the distinction

¹ *Amer. Journ. Sci.*, xl (1915), p. 193.

² Geikie, "The Carboniferous Volcanic Rocks in the Basin of the Firth of Forth," *Trans. Roy. Soc. Edin.*, xxix (1880), p. 513; and "Geology of East Fife," *Geol. Surv. Mem.*, 1902, p. 271.

depends upon the nature of the matrix in which the blocks are embedded: it is *ash* in the true agglomerate, but *lava* in an auto-brecciated flow.

Again, the resemblance between some crystal-tuffs and normal igneous rocks of the appropriate composition may be deceptively close, especially if they are altered, even in thin sections. The Ordovician volcanics of the Dolgelley district, North Wales, provide teasing examples. They are particularly massive rocks of igneous aspect, consisting essentially of plagioclase crystals embedded in a chloritic matrix. Their real nature is betrayed by the *sedimentary* characters they occasionally display, notably current bedding and wisps and lenticles of dark shale—the type of normal sediment appropriate to the environment in which deposition took place.

PART IV

PETROGENETIC CONSIDERATIONS



THE CAUSES CONTRIBUTING TO VARIATION IN ROCK-TYPE

SPECULATIONS on the larger problems of petrogenesis involving, for example, the nature of primary magma-types, can only be based upon a great accumulation of quantitative data. Of primary importance in all such speculations are the facts concerning the relative abundance and spacial distribution of different rock-types. For this purpose accurate chemical analyses are essential, and a uniform and precise nomenclature is a *sine qua non*. Information is needed also concerning the more intimate field relations between the different rocks, and the relationship, if any, which exists between an igneous suite and the local crustal conditions obtaining during the eruptive period.

More than six hundred different igneous rocks have been named, and the question arises as to how many of these consolidated from magmas of their own composition. It is impossible to give an unequivocal answer to this question; but there is general agreement that the number must be small. Field evidence makes it abundantly clear that many rocks have arisen by local differentiation from, or contamination of, some larger body of magma, the original composition of which may be unknown, but is still a legitimate matter for speculation. In problems of this kind there are almost insuperable difficulties, and in arriving at a conclusion important assumptions must be made, for which there is, in fact, little justification. The origin of a local magma is a three-dimensional problem, but the chief available data are two-dimensional only—the areas of outcrop of the several rocks involved. In the present state of knowledge there are too many “unknowns” for any final conclusions to be reached. Obviously, the best evidence for the existence of a magma-type is that it should have a widespread distribution, being well represented by numerous lava flows or minor intrusives, concerning the true magmatic origin of which there is no reasonable doubt. The evidence afforded by plutonic rocks is much less trustworthy, for by their very nature they are far more likely to become contaminated by assimilation of foreign material.

It is obviously of prime importance, therefore, that among the visible extrusive rocks basalts have at least five times the volume of all the other exposed extrusives combined. Basalt and andesite

together may be fifty times as voluminous as all the other extrusives together.¹ Bearing in mind the enormously extensive lava flows of plateau basalt type,² and the vast areas occupied by doleritic or quartz-doleritic dykes and sills, like those of the Karroo in South Africa, it is not surprising that a magma of basaltic composition is universally accepted as of prime importance. N. L. Bowen³ has urged very strongly the probability that such a basaltic magma has given rise to a very wide range—perhaps all—of the existing igneous rocks, either by differentiation or by assimilation. R. A. Daly,⁴ too, regards basalt, actually "plateau basalt," as representing primary magma. There is, however, another later theory favoured especially by W. Q. Kennedy,⁵ according to which there are two primary basaltic shells, either or both of which may become temporarily molten under suitable crustal conditions. The upper basaltic layer is believed to have a distribution corresponding with that of the continental masses, and for this reason we suggest distinguishing it as the "*subsialic basalt-magma*." Beneath lies a universal basaltic shell, of somewhat different composition, which underlies the oceans as well as the continents. This we would distinguish as "*simatic basalt-magma*." E. M. Anderson has adduced geophysical evidence which is favourable to this two-basalt hypothesis.⁶

It is significant that this hypothesis, attractive on account of its simplicity, was formulated partly to account for the existence in the Mull Tertiary volcano, of at least two magma-types. As we are dealing with *one* volcano, this fact may be interpreted as implying derivation from different depths in a stratified basaltic substratum; or alternatively, that an originally homogeneous magma-type had changed its composition with the passage of time, for one of two reasons: either by incorporation of sialic material, or by the separation of certain crystalline phases from the solidifying magma.

It is doubtful if absolute proof that one or other of these hypotheses is the correct one will ever be forthcoming; but the facts of the field associations of various rocks, the details of their microstructures and experimental studies involving silicate melts all provide valuable evidence bearing on this major problem.

¹ It is as well to combine these two lava-types for this purpose in view of the different senses in which the names are used.

² Some average analyses of plateau basalts are included in the Table on p. 304.

³ *The Evolution of the Igneous Rocks*, Princeton, 1928, pp. 5, 21, 320.

⁴ *Igneous Rocks and the Depths of the Earth*, 1933, pp. 189, 304, 395.

⁵ Kennedy, W. Q., and Anderson, E. M., "Crustal Layers and the Origin of Magmas," *Bull. Volc.*, Serie ii, Tome iii, 1938, p. 24.

⁶ Earlier writers on magma-types use the terms "tholeiitic" for subsialic, and "olivine-basalt magma" for simatic basalt-magma. Both of these terms are open to grave objection. See M. K. and A. K. Wells, "On magma types and their nomenclature," *Geol. Mag.*, lxxxv (1948), p. 349.

The broad chemical characteristics of these two magma-types were noted above (p. 304). Evidently they possess different potentialities of producing rock-types closely associated in the field, and being derived from a common parent magma, are aptly termed consanguineous or comagmatic. It is widely believed that both of these primitive basaltic magmas are capable of giving rise to suites of rocks becoming increasingly divergent from the parent "stem" with the passage of time. These suites are considered more fully below.

The processes whereby a single magma-type may give rise to a diversity of rock-types may be grouped under two headings: differentiation, or the splitting of a magma into fractions; and contamination—assimilation of wall- or roof-rock.

DIFFERENTIATION

The most favoured process of differentiation is **fractional crystallization**, the laboratory foundation for which has been discussed above (p. 166). Amongst the earliest crystals to form in a basic magma are Mg-rich olivines and Ca-rich plagioclase. It so happens that these crystals of early formation, particularly the Fe,Mg-silicates, are of relatively high specific gravity—higher in general than the liquid in which they are suspended. Therefore they may sink under the influence of gravity (gravitational differentiation), and the magma from which they formed becomes depleted of their substance, while the lower parts of the magma body become correspondingly enriched by crystal accumulations. It is obviously easier to find evidence of crystals which have been added, than of those which have been subtracted. Field evidence is overwhelmingly in favour of the gravitative sorting of olivine crystals in particular: it is found in many layered intrusions, for example the Palisades Sill, New York,¹ where the olivines have been accumulated to form a raft near the base of the sill. On a smaller scale similar evidence is afforded by a sill in the Shiant Isles²; but in this there is a steady increase in specific gravity and in the proportion of olivine, from top to bottom of the intrusion. Evidently in this case the process of gravitational sorting was arrested at an earlier stage than in the case of the Palisades Sill. Even in lava flows such as those of the Deccan, the process can be seen to have operated.

Less direct evidence for the enrichment of a magma by crystal accumulations is provided by some of the chrysophyric basalts such

¹ Walker, F., "Differentiation of the Palisades Sill Diabase," *Bull. Geol. Soc. Amer.*, li (1940), p. 1059.

² Walker, F., "The Geology of the Shiant Isles," *Quar. Journ. Geol. Soc.*, lxxxvi (1930), p. 361.

as the picrite-basalts of the oceanic islands and the picrite-dolerites of the Karoo. Bowen has pointed out that rocks of this kind are rarely, if ever, found without phenocrysts, even if the rock as a whole is a rapidly-chilled glass. This suggests that no pure liquid exists having the composition of the chrysophyric basalts, because somewhere it would give rise to a wholly glassy rock. In other words, to give a rock of this particular composition, it seems that normal basalt magma must always have olivine crystals added to it.

The calculations by Daly regarding the addition of olivine crystals to normal Hawaiian basalt-magma to yield the composition of the "picrite-basalts," have already been referred to on p. 305. The relevant analyses are quoted in the table on p. 304. The correspondence that exists between the calculated composition (normal basalt plus olivine) and the actual composition of the picrite-basalts is certainly striking, and sufficient to justify Daly's conclusion that the latter rocks have arisen by the accumulation of olivine crystals.

As we have seen, there is no difficulty in proving a case for fractional crystallization and differentiation when dealing with the rocks which have been enriched in crystals; but problems of a very different order arise when attempting to trace the subsequent history of the magmas from which those same crystals have been subtracted. A few of the trends which may be followed can be deduced with fair certainty. It is certain, for instance, that with the removal of Mg-rich olivine, the amount of Mg remaining in the liquid must decrease, and therefore the ratio $\text{FeO} : \text{MgO}$ must rise. Further, as olivine is one of the most basic coloured silicates, and anorthite the most basic of the plagioclases, their removal must result in an increase in acidity of the residuum. The content of alkalis will increase relative to Ca through the removal of anorthite. The points which have to be considered are: (1) Is the trend of differentiation likely to be towards an essentially acid and ferruginous end-product, or one essentially alkali-rich? (2) To what extremes are either of these trends to be followed in nature? Can a basaltic parent magma give rise to rhyolite as an extreme differentiate? These points can be considered only by reference to the rocks themselves. The evidence they afford is broadly of three kinds:—

1. From the association of other rock-types with basalt in the field;
2. From the order of crystallization observed in the basalts themselves;
3. From the nature of "pegmatitic" segregations in basaltic and doleritic rocks.

(1) *Association of basalts with other rock-types.*

The nearest approach to ideal "laboratory" conditions for the study of basalts is to be found among the volcanoes of the oceanic islands. The ocean floor is underlain by simatic basalt, covered by a thin layer of calcareous and deep sea sediments. It is safe to claim, therefore, that the whole association of igneous rocks in these islands must have been derived from a primary basaltic magma, admittedly with a slight chance of assimilation of, say, limestone. The rocks found on Hawaii, as described by Macdonald,¹ are dominantly olivine-basalts and basalts (without olivine), with fewer "andesites" and occasional flows of trachyte representing the extreme salic differentiates of the parent magma. The "andesites" we regard as oligoclase-basalts similar to the Scottish mugearites (p. 331). Among the rarer types are basaltic rocks containing small quantities of nepheline (nepheline-basanites), and even melilite-nepheline-basalts; as well as the cumulophyric basaltic derivatives of oceanite and ankaramite types. We would emphasize that the assemblage is essentially olivine-basaltic. It closely resembles the Carboniferous volcanic suite, embracing olivine-basalt, basalt, mugearite, trachyte and phonolite, of the Midland Valley of Scotland.

This assemblage in Hawaii is regarded by Macdonald as having evolved from a parental olivine-basalt magma (p. 304 for analysis) by long-continued crystallization proceeding under static conditions, undisturbed by orogenic earth-movements. It is typical of the existing oceanic islands, but occurs also in other "anorogenic" areas.

In contrast to the oceanic lavas, the continental plateau basalts are accompanied by occasional flows of dacite and rhyolite. This appears at first sight to support Bowen's hypothesis, that rhyolites may result from the extreme crystallization differentiation of basaltic magma. Perhaps the slight differences in composition between the oceanic and plateau-basalt magmas are sufficient to account for the different trends of differentiation in the two cases. Unfortunately this is immensely difficult to prove, for in any "continental" association of rocks a distinction must be made between two processes: *production of an assemblage of rock-types by differentiation, or by contamination of the magma by assimilation of, and mixing with, silic rocks.* In such cases evidence for derivation by fractional crystallization of a basic magma is often sought for in the smooth variation curves² obtained when the various oxides of analysed rocks are plotted against silica percentage. This type of variation

¹ *Op. cit. supra*, p. 303.

² Valuable discussions of variation diagrams are given by Harker, A., *Natural History of Igneous Rocks*, 1909, p. 118; and Holmes, A., *Petrographic Methods and Calculations*, 1930, p. 440, with refs.

diagram is probably the most useful when the rocks under consideration range from basic to acid. Once the general trend of the differentiation curves has been established, it is the usual practice to regard any analyses showing a wide "scatter" from the mean as representing contaminated rocks, or rocks which have resulted from some other subsidiary manner of differentiation. But the use of these curves has severe limitations. They certainly serve to show which rocks of a complex are genetically related, and they also show the trends of differentiation in its broadest sense. They cannot indicate, however, the process by which that differentiation was achieved. Syntexis is just as capable of giving rise to straight-line variation as, say, fractional crystallization.¹

(2) *Course of Crystallization found in Basalts and Dolerites.*

In rapidly cooled lavas and dyke rocks it is possible to trace the course of fractional crystallization through the changes in composition shown by zoned crystals, and also by the degree of idiomorphism shown by the various minerals. As an example of the former, olivine is instructive as detailed in a previous chapter (p. 46). Further, under the conditions of rapid cooling postulated, the earlier-formed crystals may not achieve equilibrium with the rest of the rock, and may persist beyond their normal stability range. Thus much of the olivine in basalts has survived on this account, even though the rock as a whole is often found to be over-saturated. With slow cooling its survival in such a rock would have been impossible: it would have been converted into pyroxene. In effect, then, rapid cooling achieves the same result as the actual removal of olivine crystals, so far as the composition of the remaining liquid is concerned. If the latter then crystallizes as a glass, it is possible for it to have the same composition as that of a differentiated liquid fraction after the removal of early formed crystals. Thus the nature of the mesostasis sometimes present in such rocks becomes of outstanding significance.

The most striking type of mesostasis is undoubtedly the so-called "micropegmatite" characteristic of the very widespread quartz-dolerites, represented in this country by those of the Whin Sill type, and elsewhere by the Karroo sills. It is not surprising, therefore, that this micrographic intergrowth of alkali-feldspar and quartz should be used as a strong argument for the view that rhyolite is the extreme fractional differentiation product of a basaltic magma of this type. According to F. Walker,² the interstitial glass of certain

¹ Holmes, A. and Harwood, H. F., "Tholeiite Dykes of the North of England," *Min. Mag.*, xxii (1929), p. 45.

² *Min. Mag.*, xxii (1930), p. 368. See also Vincent, E. A., *Min. Mag.*, xxix (1950), pp. 46-62.

"tholeiites" has a similar composition. In practice, of course, it is extremely difficult to determine the composition of minute patches of glass, using normal analytical methods. C. E. Tilley has attempted to solve the problem by determining the refractive indices of a series of glasses of known composition, which may serve as standards of comparison.¹

Unfortunately the evidence afforded by the nature of the mesostasis is conflicting. Although the residuum has a granitic (quartzofeldspathic) composition in some quartz-dolerites, and more doubtfully in some tholeiites, yet in a great number of basalts the glass is demonstrably crowded with minute grains or dendritic aggregates of iron-ore (Fig. 53). Largely on theoretical grounds the problem of iron-enrichment in the basaltic residuum has been discussed over a period of years by Fenner,² who originally stated the case in favour, and Bowen, who has argued against. Quite apart from theoretical considerations, however, the rocks concerned speak for themselves in no uncertain voice: they display iron enrichment in some instances, and alkali-feldspar and quartz enrichment in others. The root cause for these two trends of differentiation remains uncertain. If too great stress is laid upon the rôle of feldspars in differentiation problems, then the conception of a residuum having absolute enrichment in the alkalis (especially potassium) and silica necessarily follows. On the other hand it must be admitted that the variation in the coloured silicates indicates a different conclusion. It has been shown that in all the important groups of rock-forming silicates, those which crystallize early and at relatively high temperatures are Mg-rich; while those of later formation become progressively richer in iron. This variation—which is a matter of fact, not theory—lends strong support to Fenner's hypothesis. Recently confirmation of the latter has been provided by the comprehensive study of the Skaergaard intrusion in Eastern Greenland. The layering of the gabbroic members of the complex has been referred to above (p. 292). The successive accumulations of crystals which have resulted from gravitative sorting vary in the manner postulated above: in both olivines and pyroxenes the ratio of Mg to Fe falls in passing from earlier to later members of the complex. The latest which have survived denudation are the highest in the intrusion, and contain fayalite in some types and hedenbergite in others. The geological accidents which first permitted the undisturbed fractional crystallization of such a large body of basic magma at a high level in the earth's crust, and then led to the almost ideal

¹ "Density, Refractivity and Composition Relations of some Natural Glasses," *Min. Mag.* xix (1922), p. 275.

² "The Crystallization of Basalts," *Amer. Journ. Sci.*, xviii (1929), p. 225.

exposure of the resulting rocks, are quite unique. It may be partly for this reason that the phase of iron-enrichment so convincingly displayed at Skaergaard is normally not seen. It may be mentioned that there is little difference in the silica percentage of the various rocks which have resulted from fractionation in this intrusion. Wager and Deer¹ therefore suggest that the most appropriate kind of variation diagram to use for illustrating the changing composition of the component rocks is one in which the ratio of magnesia to iron-oxides is plotted against the composition of the plagioclases.

(3) *Felsic Segregations associated with Dolerites.*

W. Q. Kennedy² makes great use of the evidence provided by these felsic segregations—the so-called “pegmatitoids”—in support of his two-basalt magma hypothesis. The information he has collected largely from British Tertiary and Carboniferous dyke-rocks, suggests that simatic (olivine-) basalts give rise to alkali-rich segregations, and sub-sialic (tholeiitic) basalts to acid segregations having affinity with his calc-alkali lineage. This may indicate two different trends of differentiation from different parental magmas, but insufficient is known concerning the origin of feldspathic veins in basic rocks generally for one to use the evidence confidently.

The Ordovician dolerites of Merionethshire are cut by veins, and contain clots, of similar highly felsic material of late origin, and there is no doubt that the phenomenon is widespread. Here they have been referred to as “dolerite-aplites”—a term which is more appropriate than “pegmatitoids,” for both in mineral composition and in texture, as well as presumed origin, they are aplitic rather than pegmatitic.

Conclusions.—We may summarize the findings thus far as follows. A basic composition is the obvious choice for a single parental magma, if such is assumed to be the ultimate source of most igneous rock-types. Olivine-basalts are universally present, and must be the products of a frequently liquified earth-shell. Genuinely over-saturated basalts and their doleritic equivalents are apparently restricted to the continents, and from petrological evidence alone it is not possible to say whether they are erupted from an overlying impersistent earth-shell, or are the products of wide-spread syntaxis of sialic rocks by simatic basalt. The evidence for the differentiation of such a magma or magmas is conflicting: field evidence and geochemical research have provided convincing proof of fractional crystallization, particularly when it has resulted

¹ *Op. cit.*, p. 302.

² “Trends of Differentiation in Basaltic Magmas,” *Amer. Journ. Sci.*, xxv (1933), p. 239.

in crystal accumulations which have enriched some parts of the solidifying magma-body. The trends followed by the complementary magma fractions depleted of these crystals are more difficult to determine. In no single instance are the products of extreme fractionation seen to grade into one another, unless it be in the iron-rich gabbros, etc., of Skaergaard. Evidence for the trachyandesite-trachyte trend ("alkali trend," Kennedy) from an "olivine-basalt magma" (simatic basalt magma), or for the andesite-rhyolite trend ("calc-alkali trend," Kennedy) from subsialic basalt magma, is all of an indirect nature.

There is, in fact, powerful quantitative argument which has been directed against the theory that rocks of granitic composition originate, ultimately, in a basaltic magma. F. F. Grout¹ has calculated the amounts of magma fractions of gabbroic, dioritic and granitic composition which could be derived by fractional crystallization from 100 parts of olivine-gabbro magma as follows:—

Basaltic magma (100)	<	Liquid (50) Olivine-gabbro (50)	<	Liquid (20) Gabbro (30)	<	Liquid (10) Diorite (10)	<	Granite magma (5) Quartz-monzonite (5)
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The significant points are (1) the trivial amounts of rocks of granitic composition so formed; and (2) the fact that theoretically rocks of "Intermediate" composition should be more abundant than "Acid" rocks. These figures are obviously not in accordance with the actual amounts of syenitic, dioritic and syenodioritic rocks on the one hand, and of granitic rocks on the other, now exposed on the earth's surface. Such calculations must be used with caution, however. "Rocks of granitic composition" include rhyolites and dyke-rocks of the same composition, as well as granites; but an unknown, and probably unknowable, proportion of the last-named are believed to be not directly of magmatic origin, and therefore stand outside the scope of such quantitative estimates. Again, there is no fundamental reason why the intermediate products should be preserved at all. One of the most striking facts concerning the association of different rock-types in the field—and this is particularly true of central complexes—is the virtual suppression of intermediate rocks, and the almost constant association of basic with acid rocks. But this does not prove that in due course the intermediate products failed to appear, but merely that the local conditions prevented their survival. The great preponderance of basaltic lavas and dyke-rocks—demonstrably magmatic in both cases—over rhyolitic rocks in the same categories, is consistent with Grout's and Holmes' calculations: the overwhelming abundance of granites as compared with all other

¹ "The use of Calculations in Petrology," *Journ. Geol.* xxxiv (1926), p. 549. See also A. Holmes, "The Idea of Contrasted Differentiation," *Geol. Mag.*, lxxiii (1936), p. 228, and Nockolds, S. R., *ibid.*, p. 529.

kinds of deep-seated rocks must mean one of two things: either most granites are of non-basaltic origin; or there must be vast basic intrusives hidden beneath the exposed granites. As we shall show in the section on the origin of granites, evidence is accumulating increasingly in favour of the former alternative. Just one of the pointers in this direction may be mentioned here: in several deeply dissected granite masses, where exposure is virtually continuous for several thousand feet in a vertical sense, there is rarely, if ever, any sign of inhomogeneity or of increasing basicity with depth.

Discussion so far in this chapter has centred upon the possible trends of differentiation of basic magmas, and the petrological evidence discussed has been concerned with extrusive rocks, particularly those of basic and acid composition. The intermediate rocks, with the exception of the andesites, have been mentioned only incidentally, and the plutonic rocks hardly at all. In so far as they have been mentioned, it has only been to show that the acid and intermediate plutonites fit very badly into any theory of origin by differentiation of a basic magma. In this respect many of the plutonites may be at variance with many of the extrusives of comparable composition. It appears, in fact, that the rhyolites, dacites, andesites, trachytes and basalts have little in common, so far as genesis is concerned, with many granites, granodiorites, syenites, diorites and gabbros, despite their similarity in composition. The granitic rocks present so many problems that they are dealt with separately below; while the origin of the intermediate plutonites has already been considered in the appropriate chapters. In one important respect all these plutonic rocks may differ from their extrusive equivalents: the former frequently, and the latter seldom, show evidence of contamination by assimilation of foreign material. Some of the general aspects of this phenomenon must now be examined.

Assimilation.

Certain physical aspects of the assimilation of country-rock have already been mentioned under "stoping." Wall- or roof-rock which has been mechanically shattered and engulfed in the magma survives, for a time, in the form of angular blocks of all shapes and sizes, known as xenoliths. Initially the latter are clearly demarcated from the invading rock, and contrast with it in colour, texture and composition; but as a consequence of heating to magmatic or near-magmatic temperatures, they gradually merge their identity into that of the host rock. Two processes are involved in such assimilation. According to the composition of the xenolith, it may be incorporated by pure melting, or by reaction with the magma. On account

of the possibly highly complex composition of the xenolith as a whole, we propose to discuss the fate of individual minerals, and in the first instance restrict our attention to the rock-forming silicates.

Bowen¹ has related the reactions between magma and xenolith to those which take place between a magma and its own normally precipitated crystal phases. Thus if a magma is temporarily in equilibrium with a plagioclase of composition, say, An_{50} , which is being precipitated, then the magma will *react* with an inclusion of a more calcic plagioclase (and therefore with a higher melting point) until it conforms to the equilibrium conditions of the surrounding liquid. The latter contributes sodium and silicon, while the xenocrystic plagioclase yields up calcium and aluminium to the magma, until its composition is changed to that of the stable phase, *i.e.*, An_{50} . On the other hand, any included plagioclase richer in sodium cannot exist at the magmatic temperature, which is above its own melting point. Such a plagioclase must melt, and adds the whole of its substance to the magma. To melt a mineral, however, demands a relatively large amount of latent heat, which has to be provided by the magma. Since the latter probably has no surplus heat, unless it is being continually supplied by convectional transfer from depth, pure melting can only be achieved by a corresponding amount of crystallization—which releases latent heat.

What is true of plagioclase is equally true of all other groups of silicates belonging to continuously variable series, and probably true also of the discontinuous reaction series of Bowen (p. 172). Thus olivine, occurring in a xenolith immersed in magma precipitating biotite, would be progressively converted, in stages, from olivine to pyroxene, then to amphibole, and, if the reaction is not stopped by freezing of the magma, into biotite. Conversely, biotite immersed in olivine-precipitating magma and therefore at a temperature high above its own melting point, would melt, and in so doing would cause the precipitation of an equivalent amount of olivine, necessary to provide the latent heat of fusion. In short, xenolithic minerals high in the reaction series tend to be "made over" into those lower in the series, by reaction; while those low in the reaction series may be melted, on incorporation in magma. It follows from these general considerations that the individual component minerals in a xenolith of igneous rock will behave very differently, according to whether their melting points are above or below the magmatic temperature at the time of incorporation in the magma: some accessories may prove refractory, some essential constituents may melt, others will change by reaction as explained above.

¹ Bowen, N. L., "The Behaviour of Inclusions in Igneous Rocks," *Jour. Geol.* xxx (1922), p. 513.

Most sedimentary xenoliths differ from their igneous counterparts by having a simpler mineralogical composition, and in the extreme cases of quartzite and limestone, a very simple chemical composition also. The changes produced within the xenoliths themselves are, in the initial stages, those resulting from "contact" metamorphism of wall- or roof-rock. In highly aluminous xenoliths the well-known Al-silicates, especially sillimanite and cordierite, are produced, and even when all trace of the xenolith has disappeared, these minerals may survive, in the closest association with the normal components of the rock. Thus specimens of the Dartmoor granite, collected from near the shale roof, are normal in thin sections except for occasional clots rather richer in biotite than usual, and containing crystals of cordierite associated with red garnet. If the xenolith is of limestone, Ca-rich silicates, distinct from those occurring normally in igneous rocks, are produced. Among them garnet of the grossularite-andradite type, diopside or hedenbergite, a pargasitic hornblende and anorthite are commonly developed. Quartzite is a special case. Unless the xenolith is incorporated late in the cooling history of the magma, the temperature of the latter must be such as to render quartz unstable; but it will only melt if immersed in basaltic magma. As explained on a previous page, such melting causes precipitation of the ferromagnesian silicate stable at the magmatic temperature—often augite in basaltic magma—giving the familiar "rimmed quartzes" (p. 300). Larger quartzitic xenoliths in granitic magma behave differently, however. Here the magma takes an active hand: the diffusion of alkali ions into the quartzite leads to feldspathization. Indeed, in most of these reactions, possibly in all, both xenolith and magma contribute to the end-product, which, no matter what its original composition was, must approximate more and more closely to a rock of igneous aspect. Many painstaking studies of xenoliths have been made, involving careful analytical research; but there are inherent difficulties which are not easily overcome. Firstly, it is often almost impossible to recognize the original source-rock of xenoliths which have undergone any but the slightest reconstruction; secondly, it is difficult to be quite certain that the gains and losses deduced by comparing the xenolith with its presumed unaltered equivalent, are not due to lack of homogeneity in the rock concerned: the original composition of a xenolith can seldom be *proved*—it can only be *assumed* in many instances. Notwithstanding these difficulties, however, the fact remains that the close study of the behaviour of xenoliths in igneous magma has contributed largely to the growth of modern ideas concerning granitization.

There are many well-authenticated examples of local assimilation

which has caused contamination of the marginal facies of plutonic intrusions. The field evidence strongly suggests that some, at least, of the feldspathoidal syenites have had their origin in limestone-assimilation by granite, and in some cases by basaltic magma (p. 241); it has been suggested that assimilation of argillaceous material converts gabbroic magma into norite (p. 282); and that reaction between basic igneous xenoliths and granitic magma produces diorites and monzonites (p. 273). All of these changes have been visibly produced near the upper limit of intrusion, when the supply of heat energy must have been nearing exhaustion. It is well to realize, therefore, that similar processes must have been in operation on a much vaster scale in depth—a process which Daly has called abyssal stoping and assimilation.¹ Extensive bodies of *hybrid magma* may thus be formed by syntexis. It is not impossible that the andesites—of demonstrably magmatic origin—represent such a magma, while the less mafic sub-sialic basalt may owe its distinctiveness to assimilation of sialic rock by more mafic basic magma. There is wide scope for speculation here, with little chance of definite proof or disproof.

¹ Daly, R. A., *Igneous Rocks and the Depths of the Earth*, 1933, especially Part ii, chapters xi and xii.

NOTE

Additional references relating to the granite problem discussed in the next chapter:—

"Origin of Granite," Report of Conference held in Ottawa in 1947, *Mem. Geol. Soc. Amer.*, No. 28, 1948.

Barth, T., "Recent Contributions to the Granite Problem," *Journ. Geol.*, lvi (1948), p. 235.

Chayes, F., "Composition of Some New England Granites," *Trans. New York Acad. Sci.*, xiii (1950), p. 144.

Daly, R. A., "Granite and Metamorphism," *Amer. Journ. Sci.*, vol. 47 (1949), p. 753.

Nockolds, S. R., "The Granite Cotective Curve," *Geol. Mag.*, lxxxiv (1947), p. 19.

ORIGIN OF THE GRANITIC ROCKS AND GRANITIZATION

THE first step towards building up a reasonable theory of the origin of the granitic rocks must be based upon Daly's¹ observations that, on the one hand "granites" (notably granodiorites) are vastly preponderant over all other plutonites; and on the other, that among the volcanic rocks, the dominant type is basalt. Consideration of the geographical distribution of these contrasted rock-types led Holmes² to formulate his hypothesis that granitic rocks can originate only where a granitic shell (the sial) is already in existence. This follows naturally from the fact that granites are restricted to the continental areas, but are absent from the ocean basins. In the latter only rocks of direct basaltic parentage can be produced.

Further, even in the continents the granitic batholiths are restricted to orogenetic belts: for it is only within such regions that crustal thickening forces down the sialic rocks to depths where melting is possible. By this means a magma may be formed within the *uppermost* crustal layer (the sial), although the rocks which consolidate therefrom are of *deep-seated* "plutonic" type. By contrast, in the typical volcanic complex, although the rocks are of "volcanic" habit the magma in this case was derived from a *lower* basaltic crustal layer. There are thus good grounds for recognizing more or less distinct "plutonic" and "volcanic" associations as advocated by Kennedy.³ The **plutonic association** comprises the eruptive rocks of orogenetic regions, dominantly coarse-grained, of essentially granitic composition. The **volcanic association** includes dominantly basaltic rocks, of extrusive habit, and typically of fine-grain, occurring in stable regions subject to tension.

While it is well to recognize this distinction in a very general sense, there must be no confusion about the use of the terms involved: a "plutonic association" may include extrusive (volcanic) rocks. Further, because most granites have a different mode of origin from most rhyolites, it must not be forgotten that the acid satellitic minor intrusions around a granite pluton are often demonstrably co-magmatic with the latter, and chemical and mineralogical affinities

¹ *Op. cit. supra.*

² Holmes, A., "The Problem of the Association of Acid and Basic Rocks in Central Complexes," *Geol. Mag.*, lxxviii (1931), p. 241.

³ Kennedy, W. Q. and Anderson, E. M., "Crustal Layers and the Origin of Magmas," *Bull. Volc.*, Serie II, tome III (1938), p. 24.

may prove the same relationship between a granite and associated rhyolite flows. Similarly, a volcanic association may contain some plutonic masses, which in such cases are as often as not of gabbroic type. This is so, for example, in the Central Complexes of the Thulean Tertiary Province. In both types of association granitic rocks may be found: while they are dominant in the plutonic, they are very subordinate in the volcanic association, and fundamentally of different type. For this reason, therefore, we consider the two types of association separately.

Detailed studies of the structure, form and relationships to contiguous rocks have shown that granites, even in orogenic belts, vary widely, and certainly have not all originated in the same way. In spite of the different interpretations placed upon the evidence, some granites clearly exhibit an intrusive relationship to the country rock, and largely on the field evidence are regarded as of magmatic origin. In other cases the evidence is claimed to prove that pre-existing rocks have been granitized *in situ*, through the selective action of "emanations." These two possibilities are examined in turn.

(a) *The Magmatic Origin of Granites in Orogenic Belts.*

Whatever hypothesis is favoured, it is generally accepted that the heat energy necessary to produce a granite magma is to be found in the basaltic substratum. A considerable part of Daly's masterly treatise on the nature and origin of igneous rocks is devoted to this problem.¹ He attempts to weave a theory of the origin of batholithic granites into the overall pattern of earth-movements and orogenesis. The intimate connection between the emplacement of these masses and orogenesis is one of the paramount facts to be reckoned with. Daly considers that the downwarping of the sialic rocks forming the roots of a mountain system may lead to their ultimate melting in the hot simatic substratum. The fluid masses so formed may then penetrate upwards, partly by stoping, partly by assimilation.

Pentti Eskola considers it very probable that in addition to the wholesale melting or **palingenesis**² of sialic rocks, a process of *selective* refusion is also operative. This is a logical deduction from the geochemical considerations outlined in Part II, Chapter III. The minerals which crystallized last, and at the lowest temperatures, from the original melt, should be the first to react to a renewed rise of temperature. Orogenesis, in this hypothesis, is invoked chiefly as a filter-pressing mechanism, to squeeze out the light, low-melting-point components from the mush of more refractory crystals. Such a process operating over a considerable period of time might thus

¹ *Igneous Rocks and the Depths of the Earth*, New York, 1933, especially pp. 262 and 423.

² Also called "anatexis" by some writers.

segregate a magma of granitic composition from a very different and possibly considerably more basic mineral assemblage.¹ Obviously the *proof* of any of these processes is impossible; but the sharp transgressive junctions, the evidence afforded by the alignment of phenocrysts, and the obviously intrusive nature of the minor offshoots from the main pluton all point to the intrusion of a magma, whatever its origin.

A fact that appears to be of considerable significance in this problem is the constant close association of acid and basic rocks in igneous complexes of many different forms. This has been commented upon by many writers, including Bunsen, who based his two-magma theory on this association, and latterly Holmes² has formulated a hypothesis to explain the facts. Felsite, quartz-porphry and pitchstone occur in composite sills and dykes in association with basalt or dolerite; in larger laccolithic intrusions granophyre occurs with dolerite or gabbro, while acid veins are commonly found cutting most of the Tertiary dolerites and gabbros. Holmes noted that the cone-sheets of the Tertiary complexes converge downwards to a focus 3 to 4 miles below the surface. This focal point is believed to correspond with the apex of an upthrusting plug of basic magma—that is, with the top of a localized basaltic magma chamber. Since the thickness of the sial is considerably greater than 3 to 4 miles, it is obvious that such a magma chamber must have been situated within the sial. In view of the known lower melting point of granite as compared with basalt, it seems inevitable that extensive melting of the surrounding sialic rocks would, in these circumstances, take place, and that some acid magma would be produced by this means.

(b) *Granitization.*

The possibility that rocks of widely different type and varying composition may acquire a granitic character by essentially metasomatic processes has been strongly advocated for many years. This has particularly been the case among those concerned with the study of the Precambrian granites and gneisses of Fenno-Scandia and the other Shield areas. In these regions it is difficult to draw a line between rocks of igneous, and those of metamorphic origin, since they appear to merge imperceptibly into one another. This is the case also in Sutherlandshire where H. H. Read maintains that the higher-grade gneisses are not the products of unaided dynamothermal metamorphism of pelitic rocks, but arise through the

¹ "On the Origin of Granitic Magmas," *Petr. Mitt.*, xlii (1932), p. 468.

² "The Problem of the Association of Acid and Basic Rocks in Central Complexes," *Geol. Mag.*, lxxviii (1931), p. 247.

mixing of country rock of sedimentary origin with a siliceous, alkali, or aluminous "magma," which increases the quartz and feldspar content of the gneiss. These are the "injection gneisses" of Read, while an area characterized by these phenomena is an "injection-complex."¹ A similar process may well have operated in the case of the "Older granites" in the Scottish Highlands.

J. J. Sederholm² has described rocks of this kind, which are demonstrably of a mixed origin, as **migmatites**. The granitizing agents or "ichors" of Sederholm were described by him as having properties intermediate between an aqueous solution and a very much diluted magma, with much of it probably in a gaseous state. Detailed chemical and petrological studies of the transition between essentially metamorphic and igneous-looking rocks have been made in a few instances only. The most detailed study of the kind in a British area is that carried out by Y. Cheng³ for the rocks in Sutherlandshire. The original metamorphic rocks of the area studied include types ranging from pelitic schists and gneisses to siliceous granulites. By collecting samples strictly along the strike, it was possible to trace the effects of progressive alteration of one lithological type. Thus, in the pelitic gneisses, for instance, the original muscovite and garnet are eliminated, while plagioclase increases in amount and becomes progressively more sodic, using up some of the original free quartz in the process. The amount of biotite remains remarkably constant, although the biotite lamellae become less perfect with increasing granitization. There are other important textural changes, including increasing grain-size and the development of porphyroblastic plagioclases. At one stage myrmekite is formed. The important feature to note is that all these changes take place without any disturbance of the original schistose bedding, although certain components have by some process entered the rock, while silica has left it. The resulting granitized rock is appropriately termed a **permeation gneiss**. In Cheng's opinion the permeating agents were largely sodic solutions. Actual penetration of the gneisses by granitic fluids followed the permeation, thus giving **injection gneisses** with fairly distinct interbanding of quartzo-feldspathic layers (of "igneous" origin) and biotite-rich layers (of sedimentary origin). These are the typical migmatites. Often sedimentary structures are faithfully preserved in the granitic gneiss, so there can be no doubt as to the largely metasomatic origin

¹ "Geology of Central Sutherland." *Mem. Geol. Surv. Scotland*, 1931, pp. 88, 109, etc.

² "On Migmatites and Associated Pre-Cambrian Rocks of South-Western Finland," *Bull. Com. Geol. Finlande*, No. 77 (1926), p. 89.

³ "The Migmatite Area around Bettyhill, Sutherland," *Quar. Journ. Geol. Soc.*, xcix (1944), p. 107.

of these granitized rocks.¹ The essential point about the several theories put forward to account for these facts is this: migmatites of this type are the products of interaction between country rock and "juices" (to be non-committal) derived from a granitic magma. The latter has been considered by Sederholm and his adherents to be a necessary prerequisite for granitization.² Stated in other words, according to this view granitization can take place only if and where granitic magma is already in existence.

More or less opposed to this view is a new school of thought which favours "dry" ionic diffusion and migration along intercrystal boundaries as the granitizing process, rather than permeation of liquid or gaseous ichors, and the operation of pore fluids.³ The migration of ions is prompted by rising temperature and pressure combined: the activity of the ions depends upon the energy level. Detailed geochemical researches on contact phenomena have demonstrated that the various elements involved in the metasomatism tend to migrate in a certain order. Where a particular element or combination of elements has accumulated at the limits of diffusion within the metasomatized rock, a zone distinctive in mineral composition results, and has been termed a "front." It has been shown that in some instances, at least, a **basic front**, involving Ca, Mg and Fe is first produced and moves in advance of the acid constituents.

The most enthusiastic exponent of the concept of metasomatic fronts in this country is D. L. Reynolds who has provided several detailed studies of contact phenomena shown by the Caledonian and Tertiary intrusions in Northern Ireland. Various references are given in the last part of this book. The "basic front" phenomena are well displayed in the dark zone rich in mafic minerals frequently developed at the contact between a basic xenolith and the magma in which it is enveloped. Indeed, basic and ultrabasic xenoliths of some observers are interpreted as being due to basic fronts advancing inwards during the course of the granitization of sedimentary rock.⁴

The well-known porphyroblastic feldspars occurring in the contact zone surrounding granites are in the nature of a test case as regards granitization. A finely displayed contact between Malmesbury Shale and the granite at Sea Point just outside Cape Town provides

¹ Read, H. H., "Metamorphism and Igneous Action," Pres. Addr. to Section C, *Rep. Brit. Assn.*, Dundee Meeting, 1939, p. 223.

² We use the term "granitization" in the same wide sense as Macgregor and Wilson in their paper, "On Granitization and Associated Processes," *Geol. Mag.*, lxxvi (1939), p. 193.

³ Backlund, H., "The Granitization Problem," *Geol. Mag.*, 1946, p. 110.

⁴ See, for example, Reynolds, D. L., "The Geochemical changes leading to Granitization," *Quar. Journ. Geol. Soc.*, cli (1946), p. 389.

critical evidence.¹ Here the shale has obviously been extensively migmatized, and impregnated by material of granitic origin, whether ions or ichors is not important for the moment. The darker, more shaly portions of the mixed rock are charged with large euhedral crystals of alkali feldspar, and all the evidence suggests that they have grown *in situ*: they have not crystallized from a granitic magma, but have developed in modified country-rock in the process of undergoing granitization. Feldspar porphyroblasts of identical appearance are not infrequent in fine-grained basic xenoliths enclosed in many granites such as Peterhead, Shap, and the Jersey granites, and they convey the impression that with a slightly higher degree of alteration of the matrix in which the porphyroblasts are enclosed, the resultant rock would be close to a porphyritic granite in at least appearance.

Given that ionic transfusion of the kind postulated does in fact take place, the possibility that a boundary may be interpreted as marking the limits of diffusion by one geologist, but as an intrusive contact by another, must be faced. Possibly the interrelationships between the component minerals on either side of the boundary might provide critical evidence on this point, but such evidence is usually very difficult to interpret, and must be considered in conjunction with the detailed changes shown by serial chemical analyses of specimens collected across the contact. While these may give definite information regarding the *results* of the process, they do not unfortunately, yield information of the process itself, which is so difficult to visualize. In certain local examples, however, detailed work has shown that rocks of igneous aspect have resulted from metasomatic processes of the kind suggested. It is claimed that, as a result of progressive metasomatism, together with a piling up of energy from the emanations, a general softening and ultimately liquefaction of the material undergoing granitization will take place. Rock material in this condition is said to be **rheomorphic**, and to have been "mobilized." These are guarded terms designed to avoid referring directly to the magmatic condition; but in the last resort, a thoroughly magmatic body must surely arise in this way, and a granitic magma has been born. Indeed, it is reasonable to argue that this may be perhaps the most important process involved in the birth of a magma in the upper parts of the crust. The essential condition is that the reactions brought about by the emanations must raise the temperature of the rock-mass affected to the lowest melting-point of certain combinations of the least refractory minerals such as quartz and feldspar. In this way the necessary degree of lubrica-

¹ Mathias, M. and Walker, F., "On a Granite-Slate Contact at Sea Point, Cape Town," *Quar. Journ. Geol. Soc.*, cii (1946), p. 499.

tion may be achieved to permit either the squeezing out (by filter-press action) of the now liquid fraction, or movement of the whole mass—that is, its intrusion. If this is a true conception, it follows that it is most likely to be effective where sialic rocks are deeply depressed in orogenic regions; and this may well account for the fact that granitization phenomena are most widely and most convincingly displayed in deeply eroded Precambrian terranes. This does not preclude the possibility that the same phenomena on a less impressive scale may be produced in the uppermost parts of the crust, and even in kratogenetic complexes. Once a granite magma has been formed and has been forced upwards, partly by reason of its own deficiency in density and partly by external forces, it may be preceded by a wave of metasomatizing agents. If intrusion is relatively rapid it may follow this aureole of alteration very closely, and even overtake it, giving sharply transgressive junctions. Rather sluggish movement of the magma, on the other hand, may permit the formation of a gradational margin to the intrusion. In such circumstances any granitization phenomena would rank as contact metasomatism. On the evidence of the textural characters and chemical gradation of marginal rocks alone, it would be wrong therefore, to conclude that the whole mass has arisen by granitization *in situ*. Herein lies the great danger of assuming too much from granitization. The facts presented by the rocks themselves suggest that some such process has operated in some instances; but on the other hand, the very homogeneity of the granites whose margins may display evidence of granitization suggests that their physical state must have been such as to allow free mixing of the components. In other words, it is impossible to prove that such masses were not magmatic. It will be realized that if, in a particular case, origin by *in situ* granitization is proved, the granite is the result, not the cause, of the emanations, as has been frequently claimed. Actually this is akin to the problem of which came first—the hen or the egg. There is ample place for both magmatic and (at the appropriate level) metasomatic granites. It is important to consider each case on its merits, and to regard the evidence objectively.

On account of limited space, this has necessarily been a very brief statement of a highly controversial subject. Fortunately the reader may gather additional information from the stimulating account by H. H. Read,¹ and from the references given in the note on p. 375.

¹ "Meditations on Granite," Pres. Addr. to the Geologists' Association, in *Proc. Geol. Assoc.*, liv (1943), p. 64; and *ibid.*, lv (1944), p. 45.

PART V

*IGNEOUS ACTIVITY IN THE
BRITISH ISLES*



PRE-CAMBRIAN TO DEVONIAN IGNEOUS
ACTIVITY

ALTHOUGH it is neither advisable, nor even possible, to divorce stratigraphy entirely from an account of the igneous history of Britain, the details of the former may be largely suppressed except in so far as they bear directly on the sequence of events and the quality of the magma intruded or extruded, as the case may be, during any igneous episode. In this brief account emphasis will be laid only upon those occurrences which are of special interest, in that they have some bearing upon the problems of petrology and petrogenesis.

The igneous cycle when complete comprises:

- (i) a volcanic phase (outpouring of lava),
- (ii) a phase of plutonic (or major) intrusion,
- (iii) a phase of minor intrusion ("dyke-phase").

The products of every cycle are not necessarily completely exposed at the surface at the present time: the active period of the volcanoes may have been of short duration; the amount of lava actually extruded may have been small; subsequent erosion may have been profound. These circumstances have combined in some cases to destroy all record of the volcanic phase. In like manner the plutonic intrusions may have failed to penetrate sufficiently near to the surface to be exposed by subsequent denudation, as happened with the Carboniferous igneous cycle of the Midland Valley of Scotland, the cycle in such cases consisting of lava-flows and minor intrusions only. On the other hand, some cycles were brought to a close by a recrudescence of extrusion.

The most constant phase is that of the minor intrusions. There are, indeed, seemingly unattached dyke-phases that can only with difficulty be assigned to a particular cycle; while individual sills and dykes extend to such great distances from their volcanic centre that there is considerable difficulty in correlating them.

In Britain, volcanic activity played an important rôle in the Pre-Cambrian, Ordovician, Devonian, Carboniferous and early Permian periods, and in the Tertiary epoch.

PRE-CAMBRIAN

The later stages of the period during which the earth came into being must have been characterized by widespread and intense volcanic activity. The records of this period are lost, but during the Pre-Cambrian epoch lava was injected and extruded on a scale which has seldom been equalled since (*e.g.*, in the Keewatin and Keweenaw in the Canadian Shield).

In the area now occupied by the British Isles, volcanic action, although on a more modest scale than that characterizing the Canadian Shield, must have been widely distributed, since there are few of the comparatively small and isolated outcrops of Pre-Cambrian rocks that are not in part of igneous origin. Outstanding features are the relative abundance of acid lavas (rhyolites); the development at various levels of typical pillow-lavas; the almost invariable presence of sodic plagioclase in place of the calcic varieties more usual in the basic lavas; and the variety and complexity, both in form and composition, of the plutonic masses.

Although, on account of the absence of the usual criteria, correlation of the Pre-Cambrian formations is difficult, it is possible to distinguish an earlier (Archaeozoic) from a later (Proterozoic) period of eruptivity. The former includes the igneous rocks of Anglesey and the coast of Argyllshire, the latter, those of Shropshire, the Malvern Hills, Carnarvonshire, St. Davids (Pembrokeshire), the Charnwood Forest (Leicestershire) and some of those in the Channel Islands.

The Lavas.

In Anglesey volcanic rocks occur at three chief horizons in the bedded succession of the Mona Complex: in the Fydllyn, Amlwch and Gwna Groups basic material predominates, though rhyolitic ejectamenta also occur, chiefly in the lowest group. The basic rocks are typical pillow-lavas, consisting of rounded masses varying from six inches to a yard in diameter, and wrapped round by sediment which is sometimes jasper and sometimes limestone. The lavas are obviously submarine, and are accompanied by thin ash bands. Types that were originally glassy and others that are variolitic are well represented, and are claimed to be spilites by Greenly.¹ The feldspar is pure albite, while the coloured mineral, common augite, is somewhat better preserved than in most rocks of this kind. Occasional pseudomorphs after olivine also occur. A point of special interest is the discovery that, when traced into regions of intense metamorphism, the normal spilite passes by degrees into a rare type

¹ "Geology of Anglesey," vol. i, *Mém. Geol. Surv.*, 1919, pp. 54 and 71.

of schist consisting essentially of glaucophane and epidote.¹ These rare glaucophane-schists are restricted to one small area in Anglesey. An outlier of the Mona Complex occurs in the western extremity of the Lleyn peninsula in Carnarvonshire,² and here also spilites are well developed. Plutonic rocks of Pre-Cambrian age form part of the Mona Complex and are referred to below.

In the Tayvallich Peninsula, forming part of the low-lying coastal region of **Argyllshire**, lavas and contemporary intrusions occur in the Loch Awe Group of the Dalradian.³ That the lavas were submarine is proved by their close association with deep-water sediments, and by the perfect pillow-structure which some of them possess. The multitudinous vesicles are arranged in concentric zones, while pipe amygdales up to one foot in length spring from the base of the flows. These characteristic structures have enabled the succession to be correctly interpreted in spite of the extreme complexity of the tectonics of the region. The lavas were claimed by Flett to be spilites, and consist of albite, chlorite, carbonates and quartz. Closely connected with them, and undoubtedly contemporaneous, are transgressive sills, originally ophitic dolerites, but converted by juvenile reactions into rocks consisting of albite, urallite, epidote and sphene.

In **Shropshire** lavas and tuffs, penetrated by intrusions of leucogranite, form the Uriconian rock groups, occurring both east and west of the plateau of the Longmynd. The eastern belt includes the hills of the Wrekin and Caer Caradoc; while the western culminates in Pontesford Hill, long famous, together with the Lea Rock near Wellington, for their perlitic and spherulitic rhyolites. Andesitic ashes and flows of oligoclase-basalt also occur.⁴ Although the centres of eruption have not been exactly located there is no doubt that these lavas were erupted from volcanoes of the central type.

Lavas probably of nearly the same age constitute the Warren House Volcanic Series in the **Malvern Hills**. Although poorly exposed they show much the same range of composition as the Uriconian lavas, and include sodic rhyolites, sodic trachytes and variolitic spilites, together with tuffs.

Pebbles of acid lava closely resembling the Uriconian types have been recorded from the Torridonian sedimentary rocks of the North-West Highlands. The northerly provenance of the bulk of the Torridonian sediment, however, renders it highly improbable that

¹ "Geology of Anglesey," vol. i, *Mem. Geol. Surv.*, 1919, p. 113.

² Matley, C. A., *Q.J.G.S.*, lxxxiv (1928), and lxxxviii (1932), p. 238.

³ Bailey, E. B., *Q.J.G.S.*, 1913, p. 280, and the "Geology of Knapdale, *Mem. Geol. Surv.*, 1911, p. 59.

⁴ Boulton, W. S., *Q.J.G.S.*, lx (1904), p. 470.

these fragments were carried by coastal drift or otherwise from Shropshire to Scotland. They appear to be the only traces remaining of sheets of rhyolite, the original location of which is quite unknown. Probably they were contemporaneous with the Uriconian lavas of the more southerly localities.

The Channel Islands consist largely of plutonic and schistose rocks with rhyolitic and andesitic lavas locally well developed. The andesites are exposed in the neighbourhood of St. Helier, and on the north-east coast of Jersey. The platy habit and parallel orientation of the feldspars recall the well-known "Carnethy Porphyry" of the Pentland Hills (p. 418).

The rhyolites are more widely distributed, and are well known on account of their beautiful spherulitic and lithophysal textures.¹ Micro-phenocrysts of quartz and feldspar are sometimes present; flow banding is strongly emphasized by streams of small spherulites, generally the size of a pin's head, but occasionally much larger (Boulay Bay).² Some of the thicker flows have a perfect columnar jointing, as near Ann Port. Several of the rhyolites, e.g., near Mount Orgeuil, formerly regarded as flows, prove to be sills and dykes penetrating the granite.

The Intrusions.

Plutonic rocks of Pre-Cambrian age are widely distributed. They comprise a considerable portion of the "Fundamental Complex" of the Archaeozoic of the North-West Highlands, of the Mona Complex in Anglesey and Llyn, and of the core of the Malvern range. The Lewisian of the North-West Highlands³ is, in part, a series of plutonic complexes, comprising rocks of acid, intermediate, basic, and ultrabasic composition. Although the rocks are largely foliated orthogneisses, occasionally normal plutonic textures have been preserved. At some period subsequent to their intrusion, but prior to the deposition of the Torridonian, the region was subject to tension acting from north-east to south-west, and a swarm of north-west dykes was injected. In these all stages may be traced of the conversion of dolerite into hornblende-schist.⁴

The complex of the Lizard in Cornwall is presumably Pre-Cambrian, as are also the granites and hybrids of the Channel Islands and the granodiorites, markfieldites, diorite-porphyrries and dacites of the Charnwood Forest in Leicestershire. Of more than usual interest are the so-called **Older Granites of Scotland**. Instead of

¹ Mourant, A. E., *Q.J.G.S.*, lxxxix (1933), p. 273.

² Parkinson, J., *Q.J.G.S.*, lvii (1901), p. 220.

³ "North-West Highlands," *Mem. Geol. Surv.*, 1907, chaps. iii and iv.

⁴ *Ibid.*, pp. 85-102.

the compact, laccolithic or batholithic form commonly assumed by granitic intrusions, these bodies are of extreme complexity. They afford an excellent illustration of the process which Harker regards as of the utmost importance in the primary differentiation of igneous rocks, viz., the forcible separation of the liquid from the solid phase during the process of consolidation of a body of magma.¹

The characteristic feature of the more acid types of the older granites is their tendency to subdivision into an infinite number of small intrusions, which often permeate extensive areas and are largely responsible for the high degree of crystallization of the schists and gneisses into which they have been injected.

As a whole they are later than the main Pre-Torridonian folding movements, although the greater part of the intrusion took place when the region was still under the influence of great earth-stresses, with the result that the material of the earlier has often been separated from that of the later consolidation. The latter appears either in the form of minute sills or threads of granite intruded along the divisional planes of the metamorphosed sediments, or as pegmatite in sills or veins. The granite and pegmatite sills are as a rule foliated; while the coarser vein material is more often unfoliated. Probably the intrusions took the form of sills while the district was still affected by the great earth stresses, and that of veins as these stresses gradually ceased.

Even single small intrusions show the result of magmatic differentiation. The central core is often a slightly foliated granite; on the margin a rock of a more alkaline and foliated type predominates; while the fringing veins pass into aplite or pegmatite, which at the tips of the veins passes into almost pure quartz rock.² The complex has evidently resulted from the progressive squeezing out of the liquid portion of granitic magma consolidating under stress. Each portion is slightly abnormal in composition, but were all parts mingled the whole would make up a granite of normal composition. The intrusions can be separated into two great groups by means of the dominant feldspar; in the first (the alkali-granite type) alkali feldspar (orthoclase and microcline) predominates; in the second (the granodiorite type) the alkali feldspar is greatly subordinate to oligoclase. Certain of the latter rocks are regarded by H. H. Read as having resulted from interaction between an oligoclase-rich trondhjemitic magma and argillaceous rocks (pp. 378-9).

In addition to the "Older Granites," however, belonging to the same general period of intrusion (that is, older than the metamorph-

¹ "Presidential Address," *Q. J. G. S.*, lxxiii (1917), pp. lxxvii-xcvi.

² Barrow, G., "Geology of Lower Deeside," *Proc. Geol. Assoc.*, xciii (1912), p. 279.

ism of the Highland Schists), basic plutonic rocks in variety also occur. Originally intruded as thick sheets of gabbro and dolerite, they are now largely represented by amphibolites, "epidiorites"¹ and hornblende-schists. One great sill of this kind extends for fifty miles southwards from the coast at Portsoy. This particular sill is noteworthy as it has retained its original characters at Portsoy, where it is associated with anorthosite (an almost unique occurrence for Britain) and serpentinites, representing ultrabasic rocks, the two being in the nature of complementary differentiates.

A plutonic complex presenting many points of interest occurs in the Lizard district of South Cornwall (Fig. 132). The rocks into which the complex was intruded are highly metamorphosed sedimentary and igneous schists. The latter, which are hornblende-schists, were originally volcanic ashes and basic lavas or intrusions, and possibly represent the extrusive phase of the cycle to which the plutonic rocks belong. Evidence of the same extrusive phase is afforded by the hornblende-schists (originally basic lavas) occurring in the Channel Islands and on the mainland of Brittany. Their occurrence in these three isolated localities suggests the possibility of very widespread volcanic activity in the area now occupied by the English Channel.²

The plutonic rocks of the Lizard³ range in composition from peridotites (the earliest intrusions) to alkali-granites (the latest intrusions), the former being dominant. The ultrabasic rocks comprise dunite-serpentine, tremolite-serpentine and bastite-serpentine, the first two forming discontinuous zones round the central core of coarse-grained bastite-serpentine (Fig. 132). The peridotite probably has the form of a stratified laccolith, injected during a period of great stress which produced foliation and complicated folded junctions. The serpentine is penetrated at Coverack by a small intrusion of troctolite, which in turn is cut by veins of gabbro. These are off-shoots from a massive intrusion of gabbro which broke through the south-eastern part of the laccolith, and penetrated the serpentine in a maze of veins and dykes. The coarse grain of quite thin veins of gabbro proves this later injection to have taken place while the serpentine was still hot.

After the cooling of the gabbro, a large number of basic dykes (the so-called "black dykes") were injected. Many of these are normal olivine-dolerites, surprisingly fresh for their age, but all stages occur in the conversion of these into hornblende-schists.

¹ Wiseman, J. D. H., "The Central and S.W. Highlands Epidiorites," *Q.J.G.S.*, xc (1934), p. 354.

² Wooldridge, S. W., "Petrology of Sark," *Geol. Mag.*, lxii (1925), p. 241.

³ Flett, J. S. "Geology of the Lizard," *Proc. Geol. Assoc.*, xxiv (1913), p. 118; and "Geology of the Lizard and Menage," *Mem. Geol. Surv.*, 2nd Edn., 1946.

Others contain significant streaks and blotches of red granitic material which increases in amount in the Kennack gneisses, these having been forced into position under great pressure, and consisting of bands and lenticles of alternating granitic and doleritic composition.

Finally, red granite-gneiss, similar to the red streaks in the Kennack gneisses, was intruded into the central serpentinite as dykes and small bosses.

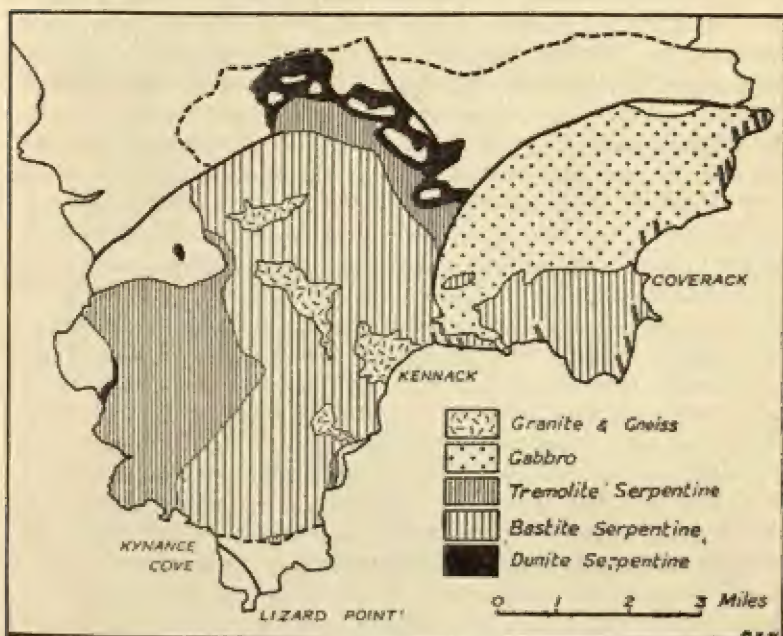


FIG. 132

Sketch-map of the Lizard Complex, Cornwall, after Sir. J. S. Flett.
Black dykes indicated around Coverack and Kennack.

The Lizard Complex is the largest mass of serpentinite in the country (20 square miles), and the rocks well illustrate the effects of injection and crystallization under pressure.

The close association of the basic and acid material in the later intrusions points to an equally close relationship when in the molten condition. It is the first of several cases to be mentioned which suggest the co-existence of basaltic and granitic magmas in the same "magma reservoir."

From the **Mona Complex** Greenly has described a series of plutonic rocks ranging from alkali-granites to dunite-serpentinites,

and including pyroxenite, gabbro, dolerite and subordinate masses of diorite. The latter are regarded as marginal modifications of the granites.¹ The Sarn granite in Lley, for long regarded as an Ordovician intrusion, is also Pre-Cambrian, and formed part of the ancient land surface on which the basal Ordovician sediments were deposited.²

In **Leicestershire** the Charnian succession³ consists largely of volcanic material, particularly in the lower part of the Middle Group, the Maplewell Series. This includes two spectacular agglomerates: a lower, "Felsitic Agglomerate" and an upper, "Slaty Agglomerate." The latter includes blocks up to five feet in maximum diameter, which indicate proximity to nearby violently explosive eruptions. These Charnian rocks are associated with a varied suite of intrusions, some few of which are represented by fragments in the agglomerate mentioned above, and their age is therefore definitely fixed. These intrusions include dacite and porphyritic microdiorite (Peldar Tor). The most extensive intrusions in the area are essentially sub-acid, and include the well-known Markfield and Groby rocks. The former gives its name to "markfieldite," a quartz-diorite with micrographic groundmass. The Pre-Cambrian age of these intrusions has recently been proved by quarrying operations in the Nuneaton district, where the basal Cambrian conglomerate is seen to rest unconformably upon an irregular surface of markfieldite, and includes large rounded boulders of the latter.⁴

The third group of intrusives in Leicestershire comprises the much-quarried Mountsorrel granite and its associated more basic derivatives. General agreement as to the age of the complex has not been reached, but it is possibly Caledonian.

ORDOVICIAN

The Cambrian Period was one of quiescence so far as volcanic activity is concerned. With the opening of the succeeding period, however, occurred the first great outburst that ushered in the widespread and long-continued activity of the Ordovician. As shown by Harker, some of these early volcanoes were grouped about the northern and southern shores of the geosyncline, which at this time occupied the British area, but others, in the centre of this tract,

¹ Greenly, E., "Geology of Anglesey," *Mem. Geol. Surv.*, 1919, pp. 90-109.

² Matley, C. A. and Smith, B., "Age of the Sarn Granite," *Q.J.G.S.*, 1936, p. 88.

³ Bennett, F. W., Lowe, E. E., Gregory, H. H. and Jones, F., "Geology of Charnwood Forest," *Proc. Geol. Assoc.*, xxxix (1928), p. 241.

⁴ Wills, L. J. and Shotton, F. W., "The Junction of the Pre-Cambrian and Cambrian at Nuneaton," *Geol. Mag.*, 1934, p. 13.

were localized by movements of elevation—the prelude to the Caledonian revolution.

The eruptions that gave rise to the pillow-lavas (spilites) of Mullion Island off the Cornish coast were possibly contemporaneous with the spilites and dolerites in the Highland Border Series occupying an analogous position on the north of the geosyncline; but the exact age of both series is still a little doubtful.

In early Arenig times eruptions in Pembrokeshire, Carmarthenshire and Southern Merionethshire gave rise to the Trefgarn, Llangynog and Rhobell Fawr Volcanic Groups respectively.

While the Trefgarn group consists essentially of andesites, the calc-alkaline lavas of Rhobell Fawr include dacites and basalts, in addition to the dominant hornblende- and augite-andesites. This locality is famous for its crystal tuffs, rich in large, though usually broken augites and hornblendes. Rhobell Fawr itself is the basal wreck of the actual volcano, which was of Vesuvian type, being built of agglomerates, ashes, lava-flows and vent-intrusions. Emanations connected with the waning phase of activity have effected a complete pseudomorphism of most of the original minerals, and have riddled the rocks with epidote and pyrite. Numerous sills crowded together west of (originally beneath) the volcanic pile indicate a well-developed "dyke-phase" to which the lithologically similar sills, dykes and small laccoliths occurring in great number in the Harlech Dome and intimately associated with the gold-bearing quartz veins in the Dolgelley district, undoubtedly belong. The rocks of the minor intrusions are those that should be associated with andesitic lavas, being hornblende-microdiorites and diorite-porphyrries.¹

In later Arenig times volcanic action became more general. To this episode belong the Coomb Volcanic Series of Llangynog in Carmarthenshire,² the Skomer Island Volcanic Series, forming the island of that name off the coast of Pembrokeshire,³ and the Lower Acid Series of Merionethshire. At the same time in the zone of *D. extensus*, submarine eruptions in the Southern Uplands of Scotland gave rise to the Ballantrae and Sanquhar Volcanic Series in the Girvan district.⁴ Of these several series, those in Merioneth and Carmarthen consist essentially of acid lavas and tuffs, those of Girvan are dominantly albite-basalts (spilites), with well-developed pillow-structure, magnificently exposed on the coast near Ballantrae and associated with coarse agglomerates. In the Skomer Island Series, soda-rhyolites, soda-trachytes (keratophyres), trachybasalts,

¹ Wells, A. K., *Q.J.G.S.*, 1925, p. 463.

² Cantrill, T. C. and Thomas, H. H., *Q.J.G.S.*, lxi (1906), p. 223.

³ Thomas, H. H., *Q.J.G.S.*, lxxvii (1911), p. 175.

⁴ Balsillie, D., "The Ballantrae Complex," *Geol. Mag.*, 1937, p. 177, but cf. *ibid.*, p. 188.

oligoclase-basalts (mugearites) and normal olivine-basalts all occur as flows.

Following a short period of quiescence during which normal sedimentation took place, the Llanvirn period witnessed the maximum of Ordovician volcanic activity; and simultaneous eruptions occurred at several centres in North and South Wales, South Shropshire and the English Lake District. In each of these localities the Llanvirn volcanic rocks rest upon deep water shales containing the *Didymograptus bifidus* fauna, which accurately dates the eruptions and proves them to have been submarine. It is possible, however, that local movements of uplift and the accumulation of great thicknesses of lava and ash enabled some of these volcanoes to emerge above sea-level and become volcanic islands. In South Wales the volcanoes soon became extinct; in Shropshire activity ceased in *bifidus* times but was renewed in the Caradocian period; in North Wales they were continuously active in one locality or another until late Caradocian times. Towards the close of the period represented by the zone of *Nemagraptus gracilis*, the volcanoes of southern Merionethshire became finally extinct, but new eruptive centres were established northwards in Snowdonia and southwards in the Wells country of East-Central Wales (Llanwrtyd Wells).¹ According to Harker the lavas and ashes of Carnarvonshire were erupted from a series of aligned cones extending south-westward from the north coast at Conway. They have long been known as the "Bala Volcanic Series." The Llanvirn and later igneous activity will be considered under the several districts concerned.

NORTH WALES

(a) **The Lavas.**—The Ordovician lavas in North Wales are of three different kinds: rhyolites (usually rich in soda), andesites and spilites. A noteworthy feature is the great development of ashes of all degrees of coarseness. These occur on all the volcanic horizons, and usually bulk far larger than the actual flows. The basic lavas are spilites, normal basalts being feebly represented. As in the Pre-Cambrian, they are characterized by pillow-structure which attains its most perfect development in the Lower Basic Group near Arthog (Merionethshire) and in the Upper Basic Group on Cader Idris. The former has a maximum thickness of 1,500 feet and the latter of about 500 feet.

East of Rhobell Fawr a variolitic basalt of normal composition (labradorite, augite and ilmenite, with the usual decomposition products) occurs in close association with typical spilites. When

¹ Stamp, L. D., and Wooldridge, S. W., *Q.J.G.S.*, lxxix (1923), p. 16.

followed to the north, the spilites give place to hypersthene-andesites, which were erupted from the Arenig Mountain centre.¹ The fact that the local volcano had built itself up above sea-level accounts for the absence of pillow structure; but in addition the lavas are of andesitic, not spilitic, type.

It is significant that spilitic pillow-lavas associated with a rhyolitic lava and ashes belonging to the *hirundo* and *bifidus* zones occur in South-West Llyn in the Carnarvonshire peninsula²; but in Anglesey and Snowdonia no volcanic rocks occur on these horizons.

In the Cader Idris district acid lavas and ashes were erupted in post-*hirundo*-pre-*bifidus* time, and again towards the close of the volcanic episode, forming in the latter case the Upper Acid Group, with a maximum thickness of 1,500 feet.³ To the north this group persists into the Arenig Mountain district.

The great majority of the rhyolitic lavas of Carnarvonshire are of Bala age. They were grouped by Harker⁴ into four series, to which he gave local names. Recently much of the area has been resurveyed by Howel and David Williams,⁵ who have shown that no lavas occur on Snowdon below the zone of *Nemagraptus gracilis* (the zone to which the highest lavas of Cader Idris and Arenig belong). Further, a thickness of some 1,600 feet of unfossiliferous, and therefore undated, strata intervene between the fossiliferous horizon and the actual base of the Snowdonian volcanics. In the Dolwyddelan Syncline east of Snowdon the highest volcanics are immediately overlain by black graptolitic slates, yielding the fauna of the zone of *D. clingani*. It follows that the volcanic episode was of relatively short duration—perhaps within the period of one zone.

The general succession on Snowdon comprises the three divisions:

3. Upper Rhyolitic Series.
2. Bedded Pyroclastic Series.
1. Lower Rhyolitic Series.

The Lower Rhyolitic Series commences with a nodular rhyolite, succeeded by well-banded rhyolites in which more quartzose and more feldspathic bands alternate. Where subjected to pressure they pass rapidly into quartz-sericite-schists. The only coloured minerals

¹ Fearnside, W. G., *Q.J.G.S.*, 1905, pp. 608-40.

² Matley, C. A., "Geology of Mynydd rhiw," etc., *Q.J.G.S.*, lxxxviii (1932), p. 238.

³ Cox, A. H., *Q.J.G.S.*, lxxx (1925), pp. 529-592.

⁴ "The Bala Volcanic Series of Carnarvonshire," *Sedgwick Prize Essay for 1888, 1889*, p. 9.

⁵ Williams, H., "Geology of Snowdon," *Q.J.G.S.*, lxxxiii (1927), p. 346; Williams, D., "The Geology . . . of Nant Peris . . .," *Q.J.G.S.*, lxxxvi (1930), p. 191; Williams, H. and Bulman, O. M., "Geology of the Dolwyddelan Syncline," *Q.J.G.S.*, lxxxvii (1931), p. 425.

are green and brown biotite, and the lavas are usually rich in the garnet, spessartine. Locally more than three-fourths (1500 feet maximum) of the Lower Rhyolitic Series consist of pyroclastic rocks, first lithic, then crystal, and finally vitric tuffs, all of the composition of potassic rhyolite. The pyroclasts are essentially glass-

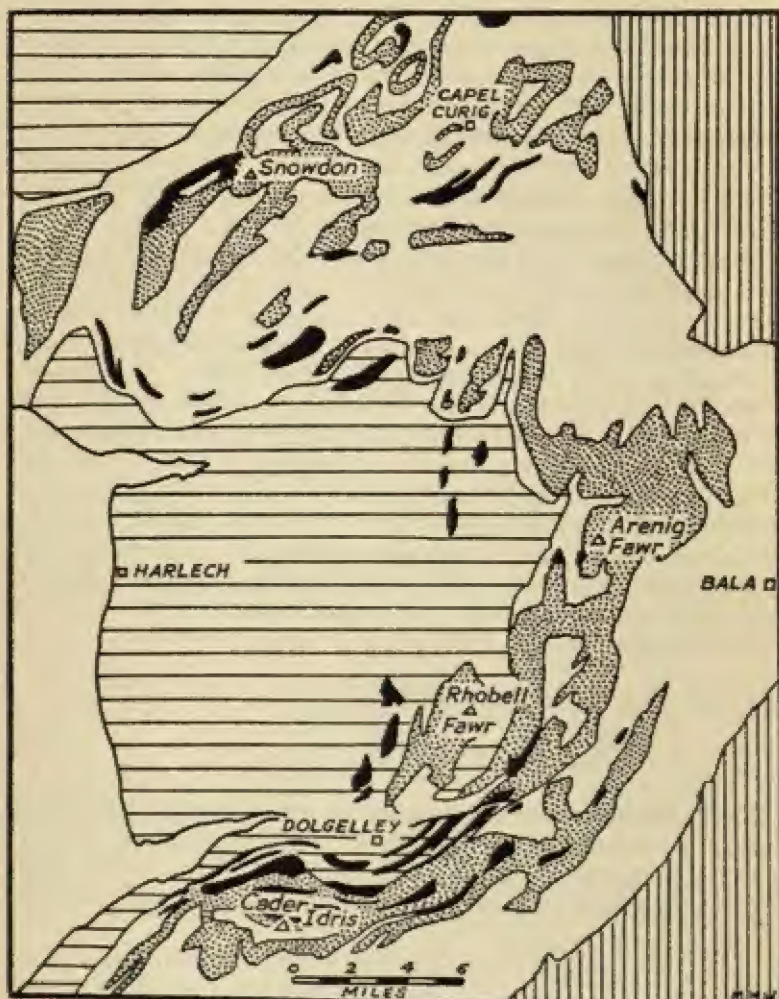


FIG. 133

Sketch-map of part of North Wales showing the distribution of the igneous rocks: volcanic, stippled; intrusive, black; Cambrian, horizontal ruling; Ordovician, plain; Silurian, vertical ruling. After *Geol. Surv.*, A. H. Cox, A. K. Wells and others.

dust rocks, bearing a very strong resemblance to the rhyolitic ashes erupted in 1912 from the Valley of Ten Thousand Smokes in Alaska.

The Bedded Pyroclastic Series includes a great variety of lavas and pyroclasts reaching 1200 feet in thickness. In the main they are basic pumice-tuffs interbedded with spilites and rare flows of rhyolite. Of special interest is the occurrence of numerous bombs of spilite and keratophyre especially abundant about Snowdon's summit. The presence of acid lavas associated with these basic rocks indicates that more than one group of vents was in operation at this period, which was that of maximum differentiation of the magma.

The Upper Rhyolitic Series consists of potassic rhyolites, though rather richer in soda than the earlier acid flows. They are poor in phenocrysts, which include orthoclase and acid plagioclase, while biotite is commonly present.

(b) **The Intrusive Rocks.**—The Lower Palaeozoic rocks of Wales are penetrated by large numbers of intrusions. On the grounds of petrographical similarity it is clear that the hornblende-microdiorites of Merionethshire represent the hypabyssal phase of the Rhobell-eruptions. Similarly the hypersthene-andesites intrusive into the rocks building Arenig Mountain must have been nearly contemporaneous with the eruptions from that centre. In both cases there is often difficulty in determining whether a particular rock is extrusive or intrusive. But in addition to these local types, there are dolerite sills of regional distribution and uncertain date. Although there were no Carboniferous or Tertiary volcanoes in Wales, intrusions of both these ages occur in Anglesey, Carnarvonshire and possibly farther south. Intense folding also took place in Wales during the Caledonian revolution, and it is possible that these earth-movements were accompanied by intrusive phenomena. Nevertheless, most of the intrusive rocks, other than those of Pre-Cambrian age, must be regarded as belonging to the Ordovician cycle. The influence of the local centres is shown even in the regional sills: those in the Arenig district show affinity with the lavas by containing hypersthene, while the feldspar is stated to be less basic than in the dolerites—andesine in place of labradorite. In those areas where the facies of the extrusive phase was spilitic, the dolerites are usually albitized, while the spilitic dolerites (which were intruded into soft mud on the sea-floor and reproduce many of the characters of the lavas) are the connecting link between the two phases. The normal dolerites are of very simple mineral composition, being plagioclase, augite, ilmenite rocks, with ophitic and ophimottled textures. The central parts of the more massive intrusions are coarse-grained and gabbroic. None of these rocks contains olivine. Quartz-dolerites and

spilitic dolerites both occur in Snowdonia and in South Merionethshire. Although in eastern Carnarvonshire the dolerites are often fresh, it is rare to find any original minerals among those of Snowdonia, where they are albitized and chloritized. In Merionethshire the dolerite intrusions are especially developed in the neighbourhood of Dolgelley, occurring chiefly as sills, particularly in the Basement Group of the Ordovician. In Snowdonia, the doleritic intrusions are dykes in the Cambrian rocks, but sills and small phacoliths in the Ordovician volcanics.

Numerous concordant intrusions of albite-dolerite occur in the Builth-Llandrindod Ordovician inlier in Mid Wales.¹ They seem to demonstrate the influence of depth of intrusion upon the form of the rock-bodies, which vary from sills in the Llanvirnian to small, widely scattered bun-shaped masses in the Llandeilian. Some appear to be laccoliths, with feeders, of the conventional type.

Large numbers of intrusions (often composite) occur in the south-west portion of the Llyn peninsula, and are intrusive into the *D. bifidus* and lower beds. Petrographically these are linked with the Palaeozoic sills, dykes and laccoliths of Anglesey. Distinctive features are the occurrence of hornblende in even the most basic types, and the large amount of olivine sometimes present. The rock-types represented include minverite (hornblende-dolerite), olivine-dolerite and hornblende-picrite. In mineral composition these rocks appear to be distinct from those occurring farther south, and Greenly claims them to be of late-Caledonian age.

The acid intrusions of Snowdonia followed the eruptive phase, and include representatives of all the commoner acid minor intrusive rocks. Phenocrysts of quartz, microperthite and orthoclase are frequently plentiful, and are embedded in a micro- to cryptocrystalline groundmass of soda-orthoclase and quartz. These acid minor intrusions are petrographically allied to the rhyolite flows. The granophyres (graphic microgranites) are characterized by the presence of augite, while the microgranites contain both this mineral and biotite. In two localities, Mynydd Mawr and Bwlch-y-Cywion, the place of these minerals is taken by riebeckite (p. 218). Mynydd Mawr is a boss-like mass three miles west of Snowdon. It is probably the plug of a volcanic vent of Bala age, marking the source of some of the lavas of Snowdon, Moel Hebog and Llwyd Mawr. A similar riebeckite-microgranite with a flow-banded rhyolitic marginal facies occurs near Llanbedrog, in the Llyn peninsula.² At Tan-y-Grisiau,

¹ Jones, O. T., and Pugh, W. J., "A Multi-layered Dolerite Complex . . .," *Q. J. G. S.*, civ (1948), p. 43; and later paper, *ibid.*, p. 71.

² Matley, C. A., *Q. J. G. S.*, xciv (1938), pp. 596 and 603.

2 miles north of Ffestiniog, there is an intrusive mass of microgranite (sometimes micrographic), $2\frac{1}{2}$ miles long. The date of the intrusion was subsequent to the hardening and cleavage of the Tremadoc rocks and may be much younger than the Ordovician. The rock is characterized by abundant quartz and poorness in ferromagnesian minerals. The feldspar appears to be largely a triclinic variety, possibly soda-orthoclase.¹

Acid intrusive rocks (granophyres) in southern Merionethshire form two massive columnar sills in the neighbourhood of Dolgelley, one building the precipitous scarp of Cader Idris, and the other occurring in the foothills to the north.²

Few of the larger intrusions in Carnarvonshire have been studied in detail: those that have, indicate their composite nature, due in some cases to successive injections and in others to differentiation in place. An example of the latter is Penmaenmawr Mountain on the north coast of Carnarvonshire, between Conway and Bangor.³ The intrusion becomes progressively more basic from the summit downwards. The upper part of the intrusion is a graphic microdiorite approaching markfieldite, while the rock building the lowest visible portion is nearly doleritic in composition, being a labradorite-pyroxene rock, with the former mineral in excess.

Shropshire and the Welsh Borders.—Ordovician andesites occur in the hills of the Shelve district, near the boundary between Shropshire and Montgomeryshire⁴ (Fig. 134). Here lavas of lower Llanvirn age form the Stapeley Hills, attaining their greatest thickness and extent on Todleth. These lavas, ashes and associated intrusive andesites contain phenocrysts of plagioclase, augite, and hypersthene in a fine microlitic groundmass. In the same area thick sheets of ash of similar composition are intercalated in the Bala rocks.

Precisely similar hypersthene-andesites occur amongst the Bala ashes of the Breidden Hills (*e.g.*, at Moel-y-Golfa, 6 miles north-east of Welshpool), which constitute an outlying portion of the Shelve area. Vesicular andesites and tuffs also occur near Builth, in the range of the Carneddau (Herefordshire and Radnorshire), where there is an outlier of Ordovician rocks.

The Ordovician rocks of Llanwrtyd Wells include volcanic material of acid and basic composition: the acid rocks are fragmental soda-rhyolites, some showing perlitic texture, while the basic rocks are typical spilites showing pillow-structure. They occur in the zone of

¹ Jennings and Williams, *Q.J.G.S.*, xlvii (1891), p. 368.

² Cox, A. H. and Wells, A. K., "The Lower Palaeozoic Rocks of the Arthog District (Merionethshire)," *Q.J.G.S.*, lxxvi (1921), pp. 283-305.

³ Sargent, H. C., *Proc. Geol. Soc. Liverpool*, xiv (1924), p. 82.

⁴ Whittard, W. F., *Proc. Geol. Assoc.*, xlii (1931), p. 322.

Nemagraptus gracilis, and are therefore contemporaneous with the Upper Basic and Upper Acid Groups of Cader Idris.¹

The comparative uniformity in the petrographical character of the lavas is reflected in the minor intrusives, of which two main types occur. The first of these, termed by Watts "intrusive andesites,"

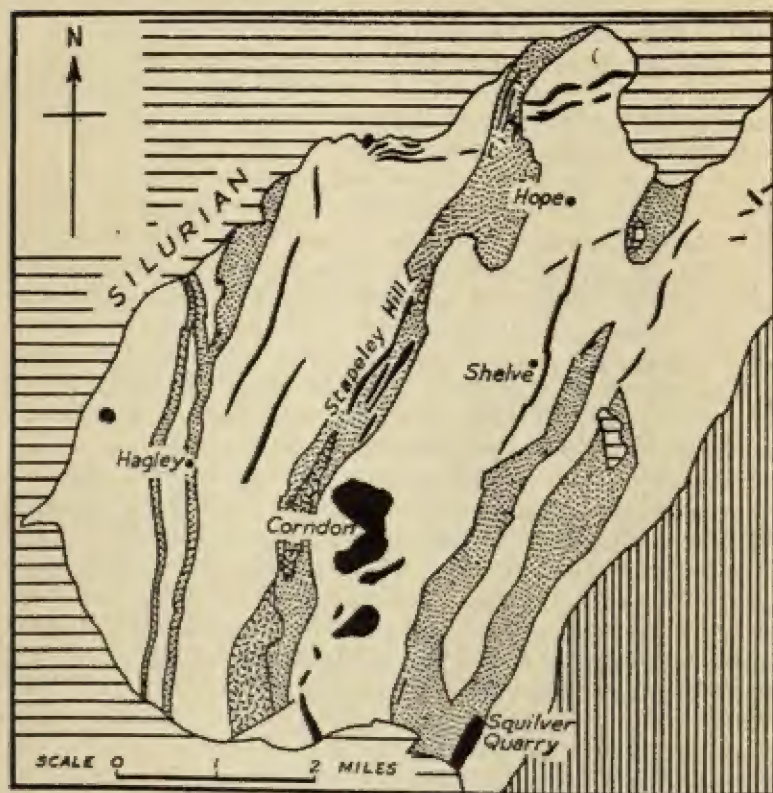


FIG. 134

M.K.W.

Sketch-map of the Ordovician inlier of the Shelfe area, Shropshire, showing the outcrops of the lavas and associated intrusions. After W. W. Watts and F. G. Blyth. Volcanic rocks stippled; basic-ultrabasic, black; intrusive andesites, small dashes; Ordovician sediments, blank.

are found in the area of the Stapeley Volcanic Series on Stapeley Hill, Llanfawr, Roundtain, and Todleth.² In the Breidden Hills they form the greater part of Moel-y-Golfa. From their lithological characters some were formerly thought to be lavas. The second type

¹ Stamp, L. D. and Wooldridge, S. W., *Q.J.G.S.*, lxxix (1923), p. 16.

² Watts, W. W., "The Geology of South Shropshire," *Proc. Geol. Assoc.*, xxxvi, 1925, p. 359.

is coarse-grained dolerite, resembling the gabbroid dolerites of North Wales. The Ordovician rocks of the Shelve area are pierced by many dykes and sills of dolerite.¹ At the Corndon and at Pitchfolds the phacolithic character of these intrusions is apparent. At the former locality the phacolith is intrusive into the *bifidus*-shales, a little below the overlying Stapeley ash-beds. In the Breidden Hills, hypersthene-dolerites containing both hypersthene and augite, and often with ophitic texture, occur at Rodney's Pillar, Criggion, Belau Bank, and Trewern, and are similar in form to the Corndon phacolith. In addition to the basic intrusives small outcrops of augite-picrite occur in the Shelve district near Shelve Church and Cwm-mawr. Some doubt exists (in the absence of direct evidence) as to their age, but as augite-picrite would be the normal, more basic differentiate of a magma which gave rise to the dolerites, and since the two types occur together in the minor intrusions of Carnarvonshire, it seems probable that the Shropshire picrites are of the same age, and belong to the Ordovician cycle.

The dolerites of this area are not all of exactly the same age: cognate xenoliths of dolerite are found in the intrusive andesites referred to above. The latter, on Moel-y-Golfa, were definitely emplaced and exposed by denudation prior to the deposition of the unconformable Llandovery beds. The dolerites of the Carneddau range, near Builth in South-West Radnorshire, cut Ordovician (Llandeilo) rocks, but are not found piercing the Llandovery beds; they are therefore considered by Woods² to be of post-Llandeilo and pre-Silurian age. Consequently some, at least, of the dolerites must be of Ordovician age. Blyth has shown that the Squilver gabbro formed a "feature" on the early-Silurian coastline, as pebbles of this rock occur in the basal Upper Valentian beach-deposits. As this gabbro metamorphoses Llanvirnian shales, the age of these intrusives is proved (Fig. 134).

The Lake District.³—The vast accumulation of volcanic material known as the Borrowdale Volcanic Series is mainly made up of andesitic lavas and tuffs, but, as in the case of the contemporaneous cycle in North Wales, a change in the character of the magma took place towards the close of the volcanic episode, the andesites and andesitic pyroclasts being succeeded by rhyolites.

The enormous thickness originally assigned to the Borrowdale Volcanic Series has been proved to be considerably over-estimated; but they probably exceed 10,000 feet. During the Caledonian revo-

¹ Blyth, F. G. H., "Intrusive Rocks of the Shelve Area," *Q.J.G.S.*, xcix (1943), p. 169.

² *Q.J.G.S.*, l (1894), p. 587.

³ Green, J. F. N., "Volcanicity of the Lake District," *Proc. Geol. Assoc.*, xxx (1919), p. 153; also Mitchell, G. H., "Borrowdale Volcanic Series, etc.," *Q.J.G.S.*, xc (1934), p. 418.

lution they were subjected to very complex folding and profound faulting.

The succession commences with true explosion tuffs, formed of material ejected during the first paroxysmal outbursts. Above these, pyroxene-andesites are followed by tuffs, and these in turn by andesites and rhyolites. The lavas are frequently brecciated, this

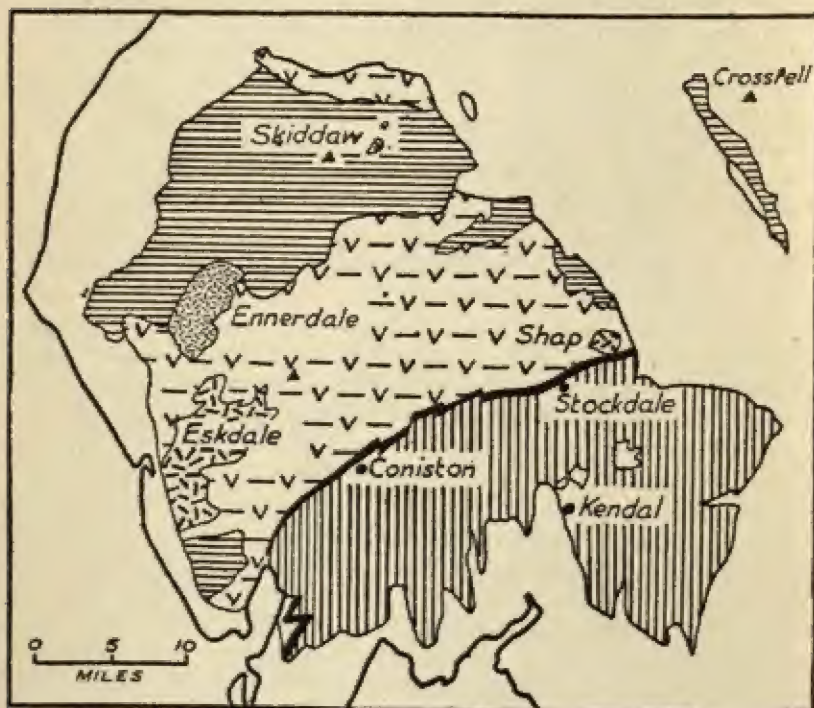


FIG. 135

Sketch-map of the English Lake District, showing the major rock-groups and the more important intrusives. Ordovician, horizontal ruling; Silurian, vertical ruling; Borrowdale Volcanic Group, V.

being accentuated on weathered surfaces, and causing a deceptive resemblance to coarse agglomerates. Petrographically the lavas are very variable, both in texture and in the proportions of the component minerals, and rock types other than the dominant andesites may be present.

The Eycott lavas that occur at Eycott Hill, one mile from Troutbeck Station, near Keswick, and in the Cross Fell range, constitute a more basic type, probably more correctly classified as basalts. Some of the members of this series are strongly porphyritic, containing

fine large crystals of plagioclase (bytownite to anorthite), also idiomorphic hypersthene altered to bastite.

Rhyolites form the highest part of the Borrowdale Volcanic Series. They are felsitic rocks, presenting strong flow structure, and occasionally containing garnets (as at Illgill Head). They occur in Langdale, on Crinkle Crag and Great Gable (Sty Head), in Long Sleddale and near Great Yarlside. The basal flow is a typical nodular rhyolite, which has been traced over a considerable area, but several of the rhyolites are intrusive.

The lowest lavas in the main Borrowdale Series, which appear to succeed the Lower Llanvirn conformably, must have been submarine, and poured out in deep water. Shallowing of the water is indicated by the strongly marked false-bedding at higher levels in certain of the ash bands.¹

In addition to the main outcrops, the Borrowdale volcanics are represented in the Cross Fell inlier by a small thickness of andesitic lava and ash (the Milburn Group) in the *Bifidus* Zone,² as well as by the overthrust masses referred to above. In the Sedbergh inlier rhyolitic flows occur in the Ashgillian.

The Lake District has its plutonic rocks in addition to a host of minor intrusives. Several of the intrusions occur at the junction of the Skiddaw Slates with the overlying Borrowdale Volcanic Series. The Eskdale granite stock (45 square miles in area), the largest intrusion in the district,³ the Buttermere and Ennerdale "granophyre," the St. John's Vale microgranite and the gabbro-"granophyre" sheet-complex of Carrock Fell all occur at this horizon. Other masses consolidated before penetrating so high. Thus the visible portion of the Skiddaw granite lies entirely in the slates of that name near to the main anticlinal axis, while the picrite of Great Cockup and many of the dolerite sills lie in the same slate series at higher levels. The famous Shap granite, on the other hand, occurs near the junction of the Borrowdales and the Conistone Limestone Series.

Very different opinions are held as to the age of many of these intrusions; the great granite masses of Shap, Skiddaw and Eskdale are commonly regarded as being of Caledonian age. This is certainly true of the Shap intrusion, but an attempt has been made to show that the other two may belong to the Ordovician cycle⁴. Similarly, the age assigned to the Carrock Fell complex varies according to different authorities from pre-Bala to Tertiary. Much depends

¹ Hartley, J. J., *Proc. Geol. Assoc.*, xxxvi (1925), p. 203.

² Shotton, F. W., "The Cross Fell Inlier," *Q. J. G. S.*, xci (1935), p. 149.

³ Simpson, B., *Proc. Geol. Assoc.*, xlv (1934), p. 17.

⁴ Green, J. F. N., *Proc. Geol. Assoc.*, xxix (1918), pp. 126-36, and vol. xxviii,

upon the correct identification of fragments of these rocks included in the basal conglomerate of the Coniston Limestone Series.

Petrographically, the rocks show a range of composition identical with that of the Welsh rocks described above, viz., from very acid



FIG. 136

Map showing the geological relations of the Ennerdale granophyre, Lake District. (After R. H. Rastall.)

"granophyres" and granites to ultrabasic picrites. Acid and basic types again predominate: there are few of intermediate composition. As in North Wales, the "granophyres" pass, towards their margins, into more basic modifications approaching markfieldite in composition (Ennerdale).¹

In the Carrock Fell complex,² occurring north-east of Keswick, the most interesting features are the sheeted form of the complex; the close association of "granophyre" and gabbro in the same composite intrusion; the presence of a hybrid zone between the two main types; the differentiation of the gabbro, which shows an increase in ilmenite from the centre to the margins, accompanied by a marked decrease in the silica-content from 60 per cent to 33 per cent.³

Of the many minor intrusions, the following may be mentioned. The Armboth dyke is a spherulitic, or granophyric quartz-porphyry, composed of bright-red feldspar (orthoclase) and dark bipyramidal quartz crystals scattered evenly through a dun-coloured groundmass containing garnets. Porphyritic microgranites occur as bosses and dykes: thus the two laccoliths of St. John's Vale, one of which is quarried near Threlkeld Station, are of this type, containing phenocrysts of orthoclase and small garnets; and dykes of a similar rock, with or without porphyritic crystals of quartz and feldspar, occur, for instance, at a number of localities: In the Westwater district there are, connected with the Eskdale and the Ennerdale masses, innumerable dykes and sills, some of which contain feldspar phenocrysts up to two inches in length. A remarkable porphyritic microgranite containing, besides phenocrysts of a red orthoclase, plagioclase and quartz, large plates of muscovite and small flakes of biotite occurs at Dufton Pike in the Cross Fell inlier, and is known locally as the "Dufton granite." A dyke of spherulitic felsite traverses the rocks of High Fell in Cumberland.

In the areas considered above the intrusions are closely associated with lavas of essentially the same petrographic type; but in other tracts where Lower Palaeozoic rocks occur this is not the case. For example, in the Cambrian inlier lying west of the Malvern Hills⁴ several sills and small bosses occur. They are not accompanied by lavas, and direct proof of their age is wanting. It is significant, how-

¹ Rastall, R. H., *Q.J.G.S.*, lxii (1906), p. 253.

² Eastwood, T., Northern England, British Regional Geology, (*Geol. Surv.*), 2nd edn., 1948, p. 26.

³ Harker, A., *Q.J.G.S.*, l (1894), p. 316.

⁴ Blyth, F. G. H., "On the Intrusive Rocks in the Cambrian inlier near Malvern," *Q.J.G.S.*, xci, 1935, p. 463.

ever, that no intrusions occur in the adjacent Silurian strata, so that an Ordovician age for the intrusions is implied. This supposition is strongly supported by the facies of the rocks, which are spilitic. The types represented are spilitic andesites, vesicular spilites and spilitic olivine-dolerites.

The Loch Borolan Complex.¹—An interesting intrusive complex occurring in the Assynt district of Sutherlandshire cuts and metamorphoses Cambrian rocks. It is affected by the Caledonian thrusts, and hence is probably of Ordovician age. In facies it differs from other intrusive rocks of this period, and, indeed, contains rock types unique in this country and uncommon elsewhere.

The complex has the form of a stratified laccolith, the members of which grade one into another, and hence were derived by differentiation in place. The highest rock exposed is a quartz-bearing soda-syenite, very near to the nordmarkite type. Beneath this, megascopic quartz is absent, and with its disappearance nepheline and its alteration products come in, while the proportion of coloured minerals to perthitic feldspars gradually increases. The central zone of the laccolith is occupied by a melanite-nepheline-syenite, while the lowest portion exposed is a melanite-nepheline-gabbro. It is probable that the base of the intrusion (which is hidden) consists of a garnet-rich pyroxenite.

The minor intrusions connected with the Loch Borolan Complex are not less interesting and include nepheline-syenite-pegmatites, aegirine-aplites ("acmite-granite" of Teall), pseudoleucite-porphyry and the problematical rocks usually referred to as borolanites. These rocks were believed to contain pseudomorphs after leucite, since they resemble very closely undoubted pseudoleucites of other (American) localities, but Shand has thrown doubt upon this identification.²

At two other localities in northern Scotland syenitic complexes occur which, from their petrographic characters, are obviously comagmatic with the Loch Borolan Complex. Indeed one of them, the Loch Ailsh Complex, is only two miles distant from the latter, and like it, is intrusive into the Cambro-Ordovician rocks outcropping to the west of the great overthrust faults which bound the North-West Highlands. The Ben Loyal alkali-complex, on the other hand, builds a picturesque mountain group lying ten miles east of the overthrust zone, in the heart of the Moine Schists of uncertain, but presumably Pre-Cambrian, age.

¹ Shand, S. J., "Loch Borolan Laccolith, North-West Scotland," *Journ. Geol.*, xlvii (1939), p. 408.

² "On Borolanite and its Associates in Assynt," *Trans. Edin. Geol. Soc.*, ix (1909-10), pp. 202-15 and pp. 376-416.

The **Loch Ailsh** mass¹ has the form of a sheeted complex or stratiform laccolith, consisting essentially of sodi-potassic syenites. The highest member contains quartz, and approximates closely to nordmarkite (p. 234). Downwards, quartz fails, as in the Loch Borolan Complex, and the dominant type is pulaskite, with colour index of 10 or over, the mafic components including aegirine and melanite garnet, with riebeckite in one variety. Still lower, the proportion of coloured minerals increases, reaching about 70 per cent in a shonkinite zone, which in turn passes down into an ultrabasic layer including biotite-pyroxenite, biotite-hornblende-pyroxenite and hornblendite. This major portion of the complex is cut by a later intrusion of ultra-feldspathic syenite, termed *perthosite* by J. Phemister, on account of its extraordinarily high content of (anti)perthitic feldspars.

The **Ben Loyal Complex** has been shown by H. H. Read² to consist of rock types closely comparable with the Loch Ailsh syenites. Pulaskite makes up the greater part of the twelve square miles exposed, but nordmarkite is also well represented.

The three complexes, together with the associated minor intrusions, comprise an alkali-province of unique type so far as the British Isles are concerned.

SILURIAN

Igneous activity in the Silurian period was restricted to feeble outbursts in one Irish (Clogher Head), one Welsh and two English localities. In the **Tortworth Inlier**, lying north of the Bristol Coalfield, two bands of igneous rock occur in Silurian strata. The higher of these is considered to be a lava-flow, since it is accompanied by tuffs, while the lower is probably intrusive. The lava is an enstatite-andesite, containing many corroded xenocrysts of quartz which, as usual, are surrounded by reaction rims of pyroxene. The rocks of the lower band are more basic, and appear to be intrusive albitized olivine-basalts.³

The only other English locality where lavas of Silurian age are known to occur is near Shepton Mallet in the eastern parts of the **Mendip Hills**. The rocks are extensively quarried for road-metal, and have been shown by Professor Reynolds to be purple and green

¹ Phemister, J., in "Geology of Strath Oykell and Lower Loch Shin," *Mem. Geol. Surv.*, 1926, p. 22.

² Read, H. H., "Geology of Central Sutherland," *Mem. Geol. Surv.*, 1931, p. 174. See also

King, B. C., "The Cnoc nan Cuilean area of the Ben Loyal Complex," *Q.J.G.S.*, xcvi (1942), p. 147.

³ Reynolds, S. H., *Q.J.G.S.*, lxxx (1924), pp. 106-11.

andesites and andesitic ashes. They contain conspicuous phenocrysts of plagioclase and bastite pseudomorphs after rhombic pyroxene.¹

Silurian volcanic rocks occur in West Pembrokeshire at Marloes, in Upper Valentian strata. They are olivine-basalt flows showing pillow-structure.

The lavas of **Clogher Head** in County Kerry differ from the other Silurian examples by being acid in composition and by including nodular and banded rhyolites. The associated sediments are of Llandovery and Wenlock age.

Mention may be made of the "green streak" in the zone of *Monograptus argenteus*, in the Skelgill Beds of the Llandoveryan of north-western England and Central Wales. This interesting band is believed to represent a distant volcanic eruption, and consists of the finest wind-blown volcanic dust.

For the rest the Silurian was a period of tranquillity: it was the calm before the storm, however, for with the close of the period came the Caledonian revolution, which is considered in relation to contemporary igneous activity in the following pages.

THE CALEDONIAN INTRUSIONS

A small-scale geological map of Scotland shows a large number of major intrusions, some of very large size. These have been termed the "Newer Granites" to distinguish them from the "Older Granites," which, as we have seen, are of Pre-Torridonian age. A better name would be "Newer Intrusives," for many rocks in addition to granites are included. It will be observed that the intrusions are aligned roughly parallel to the great faults which divide the country into regions and have the direction of the Caledonian mountain chains (the Caledonides of Suess). Doubtless the granites worked their way up into the cores of the mountains and have been exposed by subsequent profound denudation. As the intrusions came into existence at the same time as the mountain chains, that is, at the close of the Silurian period, it is best to refer to them as the Caledonian intrusions. Granites of this age are not restricted to Scotland and England: others are found in the prolongation of the Caledonian chains in Ireland (the Newry granite, for example)² and Scandinavia.

With regard to the exact age of the intrusions a difficulty arises through lack of direct evidence. With few exceptions the country-rock surrounding the intrusions is of Pre-Cambrian age. The Gallo-way granodiorites and adamellites in the Southern Uplands of Scotland are intrusive into Ordovician and Silurian rocks, so is the well-known Shap adamellite (2 square miles) in the English Lake

¹ Reynolds, S. H., *Q. J. G. S.*, lxiii (1907), p. 218.

² Richey, J. E. and Thomas, H. H., *Q. J. G. S.*, lxxxviii (1932), p. 787.

District (Fig. 137); while the largest single intrusion in the British Isles—the Leinster granite—is definitely Post-Silurian and Pre-Carboniferous in age. The small intrusions in the Manx Slates in the Isle of Man, comprising the Dhoo¹ porphyritic microgranite, and Foxdale granite, are also probably of Caledonian age. Now, had the granites been in place before the culmination of the Caledonian earth-movements they would undoubtedly show the effect of the intense pressures to which they would have been subjected. They do not do so, and hence must be younger than the acme of the revolution. In one or two cases the marginal portions of the granites show some foliation, and were therefore intruded before the earth-movements had entirely ceased. An upper limit to their age is fixed by the occurrence of boulders of the Kincardineshire granodiorite in the local base of the Lower Old Red Sandstone.² Not all of the intrusions, however, were of exactly this age, as some (e.g., the Ben Cruachan and Ben Nevis granodiorites) cut, and are therefore younger than, the Lower Old Red Sandstone lavas. The "Newer Intrusives" thus include two age-groups: an earlier (Caledonian) and a later (Post-Lower, Pre-Middle Old Red Sandstone) series. Among others whose age is not definitely proven are the Mountsorrel granite³ and associated dioritic and gabbroic intrusions. In their petrographic characters they are distinctly Caledonian.

When the petrology of the intrusions is examined it is found that there are no marked differences between the two series, such as might be used as a criterion of relative age, and in many cases it is not possible to date the intrusions precisely.

Although the intrusions are dominantly acid, many other kinds of plutonic rock are associated with the great granite bosses, either as marginal facies or as satellitic intrusions situated near to the main masses. Chief among these are diorites and monzonites; though basic types, including gabbro and norite, are not uncommon, and ultrabasic rocks are sometimes found. It has been shown that in these "plutonic complexes" the ultrabasic rocks were first injected, then those of basic composition; these were followed by intermediate rocks, and finally by the main acid intrusions.

The "Newer Intrusives" of Scotland are all either adamellites or granodiorites, with still more basic peripheral modifications in some cases (tonalites and diorites).

The **South-East and Central Highlands** are remarkable for not only the number of great intrusions found in these parts of Scotland, but also the striking difference in their mode of occurrence:

¹ Nockolds, S. R., "The Dhoo (Isle of Man) Granite," *Min. Mag.*, xxii (1931), p. 494.

² "Summary of Progress," *Geol. Surv.*, 1901, p. 111.

³ Taylor, J. H., *Geol. Mag.*, 1934, p. 1.

the irregularity and complexity of the forms assumed by the "Older (Pre-Torridonian) granites" contrasts strongly with the comparative simplicity and uniformity of the Newer Intrusives (Fig. 138). Of these several masses, the Kincardineshire adamellite is the least variable; it contains the most plagioclase and is interesting on



FIG. 138

Map of the Galloway district, showing the distribution of the granite complexes. Scale: 1 inch = 13½ miles.

account of the apophyses thrown out on its south-western margin. These rapidly pass into porphyritic microgranites.

Harker has shown that some of the Caledonian granites increase in alkalinity towards the north or north-west, indicating intrusion at a time when the country was still under the influence of the Caledonian earth-movements, and suggesting the partial separation of the products of earlier from those of later crystallization, with the migration of the latter into regions of less stress. The same

principle is illustrated by the occurrence of small intrusions of intermediate, basic and ultrabasic rocks near to the major acid intrusions. These are of earlier formation than the latter, and in several cases occur at the south-eastern side of the main masses. This is well illustrated by the Glen Tilt complex which comprises augite-diorite, tonalite, hornblende-adamellite, biotite-granite, muscovite-granite, and granite-aplite. A similar complex at Garabal Hill,¹ near the head of Loch Lomond, includes augite- and mica-diorites, norites and rocks bordering on hornblende-peridotites, now largely serpentinized, as well as tonalite and granite. This complex occurs along the south-eastern margin of the porphyritic granite of Glen Fyne.

It would be unprofitable to discuss the petrology of each of these intrusions, and only the more important points can be here considered. A constant feature is the occurrence of abundant plagioclase in addition to orthoclase in the more acid intrusions: most of the granites belonging to both age-groups are adamellites or granodiorites. This is illustrated by the so-called **Galloway** granites, which are distinguished as the Criffel, Cairnsmore of Fleet and Loch Dee *massifs* (Fig. 138).

The Loch Dee Complex comprises a central outcrop of pale coloured biotite-granite, surrounded by biotite- and hornblende-tonalite. These tonalites are crowded with sedimentary xenoliths and pass into a strongly biotitic facies where they penetrate into the wall rock. Still more basic rocks are quartz-norites and norites which are marginal in position. A zone of hybrid rocks is believed to have resulted from admixture of the sub-magmas which gave rise to the tonalite and norite respectively.²

The rock of the Cairnsmore of Fleet *massif* is somewhat less calcic, being typically a biotite-adamellite, grading into biotite-muscovite-granite. A clove-coloured sphene distinguishes the Criffel tonalite, which is extensively quarried at Dalbeattie.

In addition to the *massifs* mentioned above, smaller intrusions of granodiorite associated with tonalite and quartz-norite, and evidently of the same age and origin, are found in the Galloway district at the Mull of Galloway, on the east side of the Cree, south of Cree-town, at Cairnsmore of Carsphairn,³ Spango Water and south of New Cumnock (Fig. 137). There are also many dykes of Caledonoid trend of which the chief are porphyritic microdiorites, accompanied by a variety of acid and lamprophyric types.

¹ Dakyns and Teall, *Q.J.G.S.*, xlviii (1892), p. 104; and Nockolds, S. R.,

"Garabal Hill-Glen Fyne Igneous Complex," *Q.J.G.S.*, xcvi (1940), p. 451.

² Gardiner, C. J. and Reynolds, S. H., "The Loch Doon Granite Area, Galloway," *Q.J.G.S.*, lxxxviii (1932), p. 1.

³ Deer, W. A., "The Cairnsmore of Carsphairn Igneous Complex," *Q.J.G.S.*, xci (1935), p. 47.

The most alkaline of the Caledonian granites forms part of the **Leinster** granite (625 square miles) in south-eastern Ireland. The main intrusion is an alkali-granite with an excess of potash over soda; but in some of the subsidiary intrusions, which are doubtless co-magmatic with the main mass, soda predominates. Thus a soda-granite occurs at Aughrim, while another forms the summit of Croghan Kinshela and consists chiefly of a brilliant white sodic feldspar and grey quartz.

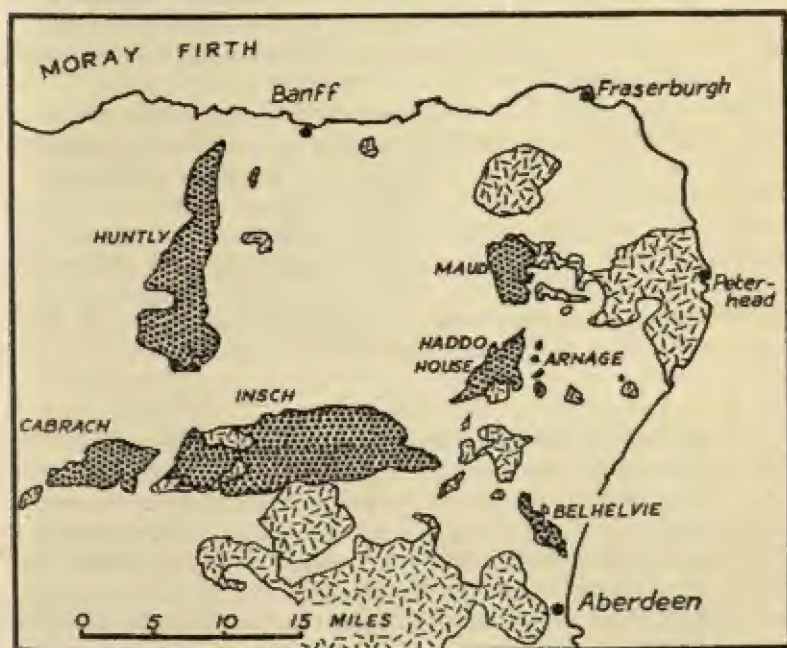


FIG. 139

Map of part of north-eastern Scotland, showing the distribution of the granitic and basic igneous complexes. (Based largely on the work of H. H. Read.)

In most cases minor intrusions in the form of dykes and sills are closely associated with the Newer Intrusives and are considered below (p. 423). Mica-lamprophyres are less widely distributed, but occur in Galloway and in the Lake District, where they are connected with the Shap adamellite (p. 356).

A second great group of Newer Intrusives includes the complexes of basic rock occurring in Aberdeenshire at Huntly, Haddo, Arnage, and Insch (Fig. 139). Although the various outcrops near Arnage are separated by a mantle of Highland Schists, they are probably

connected underground and are the exposed portions of an irregular sheet.¹ The igneous rocks are essentially norites. Between the norite and the country rock is a wide zone of "*contaminated norite*," differing markedly from both intrusive and invaded rock. The contaminated rock is crowded with xenoliths in all stages of absorption, and is usually rich in minerals not normally found in pure igneous rocks, such as garnet, cordierite (Fig. 60) and spinel. It is noteworthy, however, that some of the slides of the contaminated rock do not appear to differ essentially from normal igneous rocks. Thus one type from Kinharrachie, which consists of hornblende, plagioclase and interstitial quartz, is for all practical purposes a quartz-hornblende-diorite.

The Huntly mass² is a sheeted complex some 50 square miles in area, within which a wonderful variety of rocks of special petrological interest are exposed. They include peridotites, olivine-gabbros, troctolites, norites, as well as small granite bosses. Some of the basic rocks exhibit a striking stratification, rivalling the famous banded gabbros in Skye.

The Belhelvie Complex (Fig. 139) is essentially similar as regards its rock-types, and is best known for the troctolites (Fig. 114) which are represented in most teaching collections.³

DEVONIAN

Igneous rocks of Devonian age are important in **South Devon** and in **Cornwall**, and comprise basic and acid lavas (the latter being very subordinate to the former), together with ashes and minor intrusions (Figs. 143 and 144). The extrusive rocks cover a large area in the neighbourhood of Totnes, particularly around the village of Ashprington, and are hence often referred to as the Ashprington Volcanic series. From this locality they range southwards through Modbury, Saltash, Liskeard, and thence, swinging north of the Bodmin Moor granite, reach the north coast of Cornwall near Padstow and Port Isaac. Within this tract the igneous rocks possess peculiarities indicating community of origin: the area is, in fact, a good illustration of a petrographic province, or rather, a portion of such, since the same series of Devonian lavas, tuffs and intrusions ranges across central Europe, through the Vosges and Harz Mountains, into Moravia and Nassau.

The original character of the rocks is best preserved in the northern

¹ Read, H. H., "Petrology of the Arnage District," *Q.J.G.S.*, lxxix (1923), pp. 447-86.

² Read, H. H., *Geol. Mag.*, 1924, p. 433, and "Geology of Banff, Huntly and Turriff," *Mem. Geol. Surv.*, 1923.

³ Stewart, F., "The Gabbroic Complex of Belhelvie, Aberdeenshire," *Q.J.G.S.*, cli (1947), p. 465.

part of the area, but towards the south the rocks become more and more affected by the Armorican earth-movements; indeed, in the Plymouth district they are so altered that their recognition as of igneous origin is difficult, while it is usually quite impossible to distinguish between lavas and intrusions.

In south-eastern Devonshire the eruptions commenced in early Middle Devonian times. The sites of the volcanoes have not been located, but it is clear that they must have been situated at a considerable distance from the shore-line of the Devonian Continent. Consequently the lavas are submarine, and are interbedded with limestone and other normal marine sediments. The basic lavas are all spilites showing pillow-structure and the high degree of vesicularity characteristic of these rocks. These features are particularly well exhibited at Chipley, where a thickness of 70 feet of pillow-lava is exposed.¹

In the Plymouth-Liskeard district the lavas are much decomposed, especially those belonging to the Middle Devonian. Those interbedded with the Upper Devonian sedimentary rocks are slightly better preserved, and are seen to be chiefly spilites. Farther to the north, in the neighbourhood of Tavistock and Launceston, similar rocks occur in the Upper Devonian—Lower Culm.

On the north coast of Cornwall no igneous rocks are found in the Lower and Middle Devonian, but in the Frasnian division of the Upper Devonian they attain to their maximum development: at Pentire Point, near Padstow, the thickness of pillow-lava, well exposed in the sea-cliffs, exceeds 250 feet.²

In addition to the abundant basic flows, others of acid composition occasionally occur in the neighbourhood of Newton Abbot and Ivybridge. Like the spilites with which they are associated, a high soda-content is characteristic, and the rocks may be referred to the sodic rhyolites (quartz-keratophyres of some authors). They are much brecciated, but it is difficult to decide whether this is the result of flow-movements in an extremely viscous lava, or of explosions in the vents.

The minor intrusions range in composition from basic to ultra-basic, and comprise three chief types; dolerites, minverites and picrites.

The dolerites are coarse-grained, non-vesicular rocks forming sills, in some of which large quarries have been opened for road metal, as at Trusham in the Newton Abbot district.³ The augite is a normal

¹ "Geology of Newton Abbott," *Mem. Geol. Surv.*, 1913, pp. 54-56.

² Dewey, H., *Proc. Geol. Assoc.*, xxv (1914), pp. 165-73.

³ "Newton Abbot," *Mem. Geol. Surv.*, 1913, pp. 59-63.

brown variety, which in some specimens merges into titanaugite. No basic plagioclase is found in these rocks, but albite, some of which is primary, usually makes up nearly the whole of the feldspar present. An aplitic modification of the albite-dolerites is not uncommon. It occurs in veins and segregations, and consists essentially of micropertthitic feldspars.

The minverites are feebly developed in Devonshire, but are the dominant intrusive types in Cornwall, both in the neighbourhood of Plymouth and in the Padstow district. At the latter locality they form sills up to 70 feet in thickness. The type-specimens come from the Rock Quarry, St. Minver, on the Camel Estuary. In these rocks barkevikitic amphibole is the dominant coloured mineral, though it is sometimes accompanied by olivine, titanaugite and bronze-coloured biotite. As in the lavas, the feldspar is chiefly albite, but some anorthoclase occurs in addition. The texture varies considerably: some rocks are coarsely ophitic; in others there is a tendency towards idiomorphism of the dark minerals; while others again are compact, fine-grained and resemble some camptonites.

No fresh olivine has yet been found in the basic intrusions, but serpentinous pseudomorphs, embedded in the pyroxene, are not uncommon in the dolerites. By increase in the amount of olivine, at the expense of the feldspar, there is a gradation to picrites, a few of which occur in this cycle. Teall has described the augite-picrite of Menheniot (Clicker Tor). Typical hornblende-picrite is found at Molenick in the Plymouth district, while augite-picrite occurs at Highweek in the Newton Abbot district.

Each of these intrusive types strongly resembles the contemporaneous rocks in the continuation of the province in Central Europe.

THE OLD RED SANDSTONE LAVAS

Igneous activity during the Devonian Period was by no means restricted to the submarine eruptions that occurred in the area now occupied by Devon and Cornwall: in northern Britain and north-western Ireland contemporary volcanoes poured out an enormous quantity of lava and ash of quite different types from those described above, although of the same age. The Old Red Sandstone cycle is complete, comprising an extrusive phase, the dominant type being andesite; a phase of major (plutonic) intrusion, during which some of the largest granite masses in this country came into being; and a phase of minor intrusion, when porphyritic microdiorites were injected as dykes.

The lavas were poured out from volcanoes of the central type located along lines of instability connected with the Caledonian

earth-movements. One series of cones bordered the Midland Valley of Scotland on the north, and extended across into Ireland. Another series bordered it on the south (Fig. 140). Relics of the outpourings from the former occur in the **Ochil** and **Sidlaw Hills**, and the Lorne district of Argyllshire, including **Ben Nevis** and **Glencoe**; while

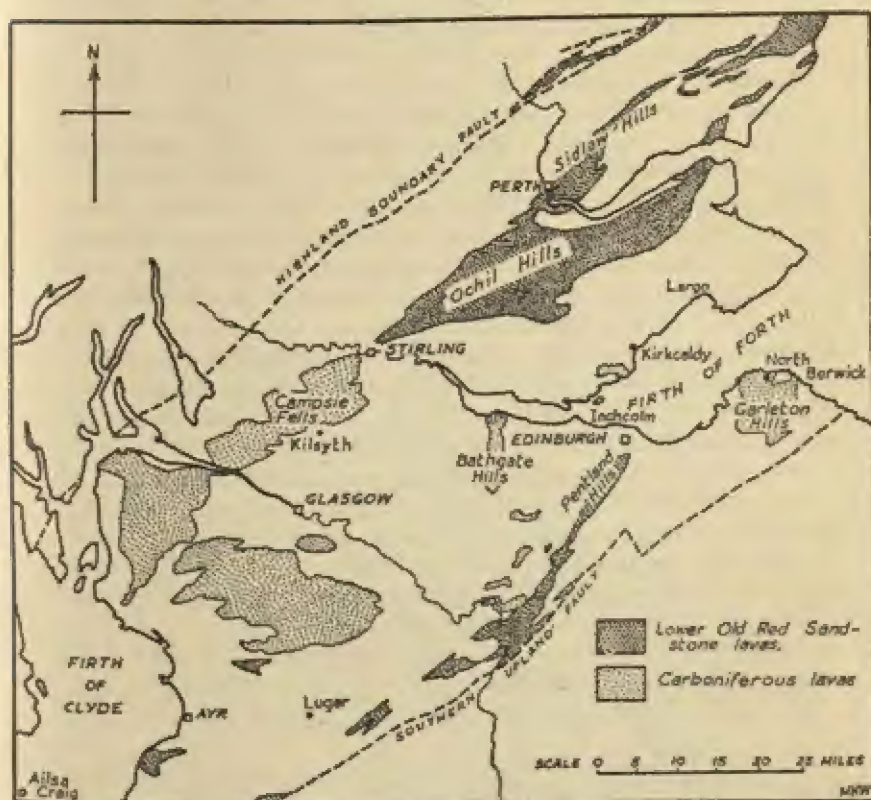


FIG. 140

Map of the Old Red Sandstone and Carboniferous lavas of the Midland Valley of Scotland. (Based on maps of the Geological Survey.)

the latter are represented by the lavas, ashes and intrusions of the **Pentland Hills**, the **Braid Hills**, the **Cheviot Hills** (Fig. 142), and a small area in North Ayrshire.¹

The volcanic rocks rest upon an uneven eroded land surface consisting of schists in the South-West Highlands, and folded Silurian rocks in the Cheviots and Central Lowlands. Locally basal con-

¹ MacGregor, A. G., in "Geology of N. Ayrshire," *Mem. Geol. Surv.*, 1930, p. 28.

glomerates and breccias are intercalated, which are of interest inasmuch as they contain pebbles of lava, thus proving the existence of even earlier flows. The basal sediments have yielded fragmentary plant remains (*Psilophyton* and *Pachythecca devonica*)¹ in Lorne and Glencoe, which have satisfactorily proved the age of the overlying volcanic rocks as Lower Old Red Sandstone. Further, they are succeeded unconformably by Upper Old Red Sandstone in some localities.

The lavas themselves are frequently brecciated (block-lavas) and in some cases can only with difficulty be distinguished from the interbedded agglomerates. The proportion of pyroclasts to lavas is small, showing that the eruptions were not of a violently explosive type. It is probable that the lavas were in part laid down under sub-aerial conditions: the upper portions of the flows are frequently reddened, due to atmospheric weathering between one eruption and the next. Occasional shales and sandstones occur interbedded with the lavas, and sand-filled crevices and "sandstone dykes" are characteristic.

Although the succession has been the subject of careful study at many localities, it is impossible to correlate individual flows except over restricted areas, because the lavas erupted from neighbouring centres differ in composition, although the volcanoes were so close to one another that their products interdigitate. The dominant type of lava is a basic andesite (verging on basalt), and this is interbedded with rhyolite, trachyte and basalt. The succession established at Glencoe may be regarded as typical. This comprises the following:

	Feet
7. Andesites and rhyolites	about 300
6. Shales and grits	50
5. Rhyolite	250
4. Hornblende-andesites	900
3. Agglomerate and shale	250
2. Rhyolites	450
1. Augite-andesites	1500

The more basic of the lavas contain small red pseudomorphs after olivine, and bear a close resemblance to Harker's "Mugeary type" of basalt. In others the olivine is less abundant and is accompanied by pale green augite. In the typical augite-andesites only the latter occurs as phenocrysts. Basalts and basic andesites with phenocrysts of feldspar are uncommon in the west (Glencoe and Ben Nevis), but a very distinctive type occurs near the top of the succession in the Pentlands. This rock is distinguished as the "Carnethy porphyry."

¹ "Geology of Ben Nevis and Glen Coe," *Mem. Geol. Surv.*, 1916, p. 89.

and is particularly rich in fluxionally arranged, platy phenocrysts of plagioclase. One of the basic lavas in Glencoe contains the rare red variety of epidote, withamite, occurring as blood-red crystals in druses.

The less basic lavas include enstatite-, hornblende- and mica-andesites. In addition to the phenocrysts of coloured minerals, these andesites are rich in porphyritic feldspars, ranging in composition from andesine to labradorite. The Cheviot lavas¹ total some 1200 feet in thickness, and include dominant augite-hypersthene-andesites, glassy andesites, trachyandesites and curious types termed by the Survey Officers "oligoclase-trachytes."

In chemical composition the lavas noted above are evidently closely related to the intrusive augite-diorites, kentallenites and monzonites belonging to the subsequent plutonic phase. Some of the lavas are rich in orthoclase, particularly certain flows from Lorne, and consequently are to be regarded as trachybasalts or trachyandesites, according to their degree of basicity.

The dacites connect the acid lavas with the hornblende- and mica-andesites, from which they differ chiefly in the occurrence of numerous phenocrysts of quartz. They are so closely similar in appearance to many of the rhyolites, that in some districts the two types of rock have not been differentiated in the field.

The rhyolites are chemically related to the most acid granites and microgranites of the succeeding phases, but vary considerably in texture among themselves. Some show beautiful flow-texture, others are cryptocrystalline through devitrification of an originally glassy rock, while many are spherulitic. The phenocrysts include albite, orthoclase, biotite and quartz. It is usually the case that the more acid andesites grade into rhyolites, but in the Pentland Hills they are associated with potassic trachytes.

THE OLD RED SANDSTONE MAJOR INTRUSIONS

Reference has already been made to the general characters of the post-Lower Old Red Sandstone major intrusives. They range in composition from thoroughly acid granites to thoroughly basic rocks rich in olivine, while locally feldspar-free ultrabasic types occur. Outcrops of acid rocks are far more extensive than those of intermediate and basic composition, and in volume, the former are in large excess over the latter, *i.e.*, the magma, as represented by the plutonic rocks, was essentially acid. Direct evidence of the age of these intrusions is sometimes forthcoming. Thus on Ben Nevis, in

¹ Carruthers, R. G. and others, "Geology of the Cheviot Hills," *Mem. Geol. Surv.*, 1932, p. 8.

Glencoe and the Cheviot Hills, the granites cut the Old Red Sandstone lavas, and must therefore be younger than the latter. In other cases, however, such direct evidence is wanting, and the age of many of the granite masses in the Highlands is therefore largely a matter of speculation. In many cases it is not possible to make a more precise statement than "post-Silurian, pre-Middle Old Red Sandstone." Facts of general interest in connection with the Old Red Sandstone major intrusions are: their large size; their composite nature; the occurrence of satellitic intrusions of basic to ultrabasic composition; and the sharp, regular character of the highly inclined junctions with the country-rock.

In these several particulars, the intrusions differ from the so-called "Older Granites" of Scotland.

With regard to the form of the major intrusions, it is clear that many are true bosses as defined on p. 157. The outcrops are in many cases roughly circular, and the contacts are steeply inclined, while the manner in which they cut across the bedding and foliation planes of the country-rock is strikingly shown on the geological maps. On account of the marked similarity of composition between rocks of this age over very extended areas, it may be suspected that they are connected underground, and that the bosses are cupolas rising from the tops of a batholith. The intrusions occurring at Ben Nevis and Glencoe are of rather special interest as they bear evidence of an unusual method of intrusion.

The granites of Glencoe form a part of one of the greatest intrusive masses in Scotland, known as the Etive Complex¹ (Fig. 141). The earliest and main portion of this complex is the Moor of Rannoch granite; this is cut by the Ben Cruachan granite, and the latter again by the Starav boss. The evidence seems clear that the dyke-phase, to be referred to below, supervened between the injection of the Cruachan and Starav masses. We thus have an interesting case of one granite boss penetrating another of somewhat earlier date. It is believed that the second injection was consequent upon the down-faulting of a cylindrical plug of country-rock (in this case the Cruachan granite). It has already been shown (p. 155) that cylindrical or conical fractures may be produced above the top of an advancing plug of magma. In at least three cases in the area under consideration, such fracturing was followed by collapse or foundering into the magma underlying the tract surrounded by the fault. Such phenomena have been termed cauldron subsidences.² In Glencoe and on Ben Nevis the lavas owe their preservation to such "piston-faulting" (Fig. 71). In the latter locality, the igneous *massif* consists of three

¹ Anderson, J. G. C., "The Etive Complex," *Q.J.G.S.*, xciii (1937), p. 487.

² Clough, C. T., Maufe, H. B., Bailey, E. B., *Q.J.G.S.*, lxxv (1909), p. 611.

approximately concentric zones: the outer granite, the inner granite and, in the centre, the outcrop, roughly circular in shape, of the lavas resting upon a floor of schist. As in the Etive Complex the

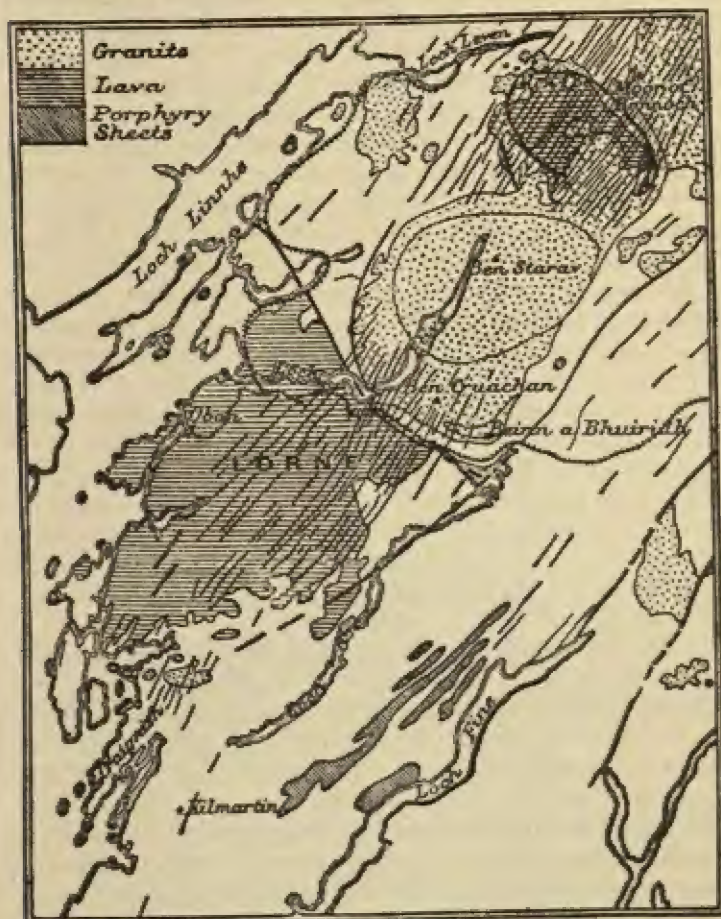


FIG. 141

Sketch-map of the volcanic district of northern Argyllshire (Glencoe), showing the distribution of the lavas of Old Red Sandstone age and of the dykes (chiefly porphyritic microdiorites: cf. p. 264), in relation to the Etive granite complex. The Highland schists are left white. Faults are shown by heavy black lines. (After Clough, Maufe, and Bailey: "The Cauldron Subsidence of Glencoe.")

dyke-phase intervened between the injection of the outer and the inner granites. In the light of the clear evidence obtained at Glencoe, it is at least probable that cauldron subsidence operated on three

occasions at Ben Nevis, while the outer granite itself consists of three fractions forming arcuate outcrops.¹

With regard to the petrography of the major intrusions it should be noted that the dominant types are adamellites and granodiorites,² i.e., a large proportion of the feldspar consists of acid plagioclase, which is typically oligoclase. Locally the rocks grade into tonalite and quartz-monzonite (Banat type). The larger intrusions are too numerous to be described in detail, but the Etive Complex may be regarded as typical. The earliest member of the main complex is the most basic: the Moor of Rannoch rock is essentially granodiorite, consisting of microperthite, oligoclase, quartz, hornblende and biotite, while sphene is a prominent accessory. The marginal zone is more acid, being free from hornblende, and is characterized by a porphyritic texture. The Cruachan granite is in the main an adamellite, containing cryptoperthite, zoned plagioclase and quartz. The dominant coloured constituent is green hornblende, but this is accompanied by biotite, either intergrown with, or moulded upon the amphibole. The Starav granite is still more acid, and coloured minerals are less abundant, though the two feldspars are still present in approximately equal proportions, the rock being an adamellite. More acid still is a high level modification of the Cruachan mass, in which the coloured mineral (biotite) is very subordinate, the rock consisting of quartz and alkali-feldspars (chiefly perthites). Leucogranite of this type seems to be widely distributed among the "Newer Intrusives."

The Cheviot granite³ (Fig. 142) is a partly unroofed laccolith, the exposed area being 22 square miles. It is noteworthy on account of the modification it has undergone through assimilation of the country rock. The normal rock is a pink micrographic granite deficient in coloured minerals; but in places, particularly where the magma has penetrated *lit-par-lit* into the surrounding lavas, it is highly contaminated, of dioritic aspect and locally contains augite.

In the granophyric type biotite is the only coloured silicate; but in the marginal facies biotite is accompanied by pyroxene, both diopsidic augite and hypersthene being present; quartz may amount to a few per cent only, and may be absent. Thus these marginal rocks are, in fact, not granites at all, but monzonites and diorites,

¹ Anderson, J. G. C., "The Marginal Intrusions of Ben Nevis," *Trans. Geol. Soc., Glasgow*, xix (1935), p. 225.

² The student should note that in the "Geology of Ben Nevis and Glencoe," *Mem. Geol. Surv.*, 1916, the rock-names are not used in exactly the same sense as in this text-book.

³ Carruthers, R. G. and Others, "Geology of the Cheviot Hills," *Mem. Geol. Surv.*, 1932, p. 87. Thomas, H. H. in "Geology of the Cheviot Hills," *Mem. Geol. Surv.*, 1932, p. 90; Jhingran, A. G., "The Cheviot Granite, etc.," *Q. J. G. S.*, xcvi (1943), p. 241.

which have obviously been derived, by contamination, from granitic magma.

Passing now to the consideration of the more basic intrusions, it is noteworthy that these form small bosses, as a rule not far removed from the great granite intrusions described above. We shall again largely restrict our attention to the South-West Highlands, where the age of the intrusions is not questioned. The chief types of intermediate, basic and ultrabasic rocks occurring in Argyllshire and the adjacent islands, are shown in tabular form below.

<i>Intermediate.</i>	<i>Basic.</i>	<i>Ultrabasic.</i>
Augite-diorite.		
Hornblende-augite-diorite.	Kentallenite.	Augite-picrite.
Monzonite.		
Hornblende-diorite.	Hornblende-	Hornblendite.
Appinite.	gabbro.	Hornblende-peridotite.

The dominant rock types are those in which pale green augite (diopside or malacolite) is the characteristic coloured constituent: normal hornblende-syenites and diorites are rare among the intermediate rocks; but many of the meladiorites are rich in hornblende and have been termed "appinites."¹ With decreasing feldspar these rocks grade into hornblendite, and with the incoming of olivine into hornblende-peridotite of the Cortlandt type. In Colonsay, one of the Hebrides adjacent to the mainland, a similar series of intrusions has been described by the Survey.² Direct evidence of the age of these intrusions is wanting, but on the ground of petrographical similarity they also are referred to the Old Red Sandstone. Since, in some cases, they are intrusive into breccia or agglomerate it has been suggested that they mark the site of explosion-vents and are themselves vent-intrusions.

THE LOWER OLD RED SANDSTONE DYKE-PHASE

One of the most striking features of this igneous cycle is the remarkably well-developed dyke-phase which in general followed, though to some extent it overlapped, the plutonic phase. The dyke-phase reaches its maximum development in western Argyllshire, where a regional tension acting in a N.W.-S.E. direction gave rise to a series of closely spaced parallel fractures, up which the magma rose, thus forming the **Etive swarm** of N.E.-S.W. dykes (Fig. 141). It will be noted that the dykes are restricted to a comparatively narrow belt of country very much elongated in the direction of the dykes themselves. There can be little doubt that this tract was

¹ "Ben Nevis and Glencoe," *Mem. Geol. Surv.*, 1916, p. 168.

² "Geology of Colonsay and Oronsay," *Mem. Geol. Surv.*, 1911, pp. 28-37.

located above the body of magma, the comparatively thin roof of which would determine the position of a belt of weakness in the crust. The magma of this reservoir must have been closely similar in composition to the lavas poured out during the extrusive phase, since the dominant type among the dyke-rocks is porphyritic microdiorite together with non-porphyritic types.¹ In the former rocks highly idiomorphic crystals of hornblende and biotite, together with plagioclase ranging from oligoclase to andesine, occur as phenocrysts. The same pale green augite which characterizes the more basic plutonic intrusions is occasionally found in the dykes, and is sometimes accompanied by orthorhombic pyroxene. In addition to the microdiorites more acid, as well as more basic types are found. The former include porphyritic microgranites, with phenocrysts of quartz and alkali-feldspar, set in a variable groundmass. The proportion of coloured minerals in these rocks is low, and they are evidently closely related to the leucogranites, being themselves porphyritic aplites rather than "undifferentiated" rocks. Acid dykes without phenocrysts and deficient in dark minerals are not uncommon; it seems reasonable to regard them as aplites complementary to the lamprophyres which also occur. The latter are of two different ages: some occurring as horizontal sheets are probably the earliest intrusions in the cycle, while others are clearly members of the Etive and Ben Nevis swarms. As might be expected, the dominant types are rich in hornblende (hornblende-lamprophyres), sometimes with olivine in addition (olivine-hornblende-lamprophyres), while mica-lamprophyres with augite and olivine are but feebly represented.

The dyke-phase in the Cheviot Hills includes two swarms differing slightly in age, but widely in trend. They freely cut the lavas, but few can be traced into the granite, which appears to be later than the majority of the dykes. The chief type is almost identical with the dominant type of lava, being augite-hypersthene-microdiorite or andesine, according to grain-size.

In conclusion, the igneous rocks of Lower Old Red Sandstone age in this country may be regarded as an excellent example of an igneous cycle. The magma was essentially calc-alkaline in facies and, although the three phases were distinct, the products are so closely related in composition as to leave no room for doubt as to their common origin. The contrast between the Devonian igneous rocks of South-West England and the Old Red Sandstone igneous rocks of Scotland and the Borders is to be accounted for in part by the differences in the conditions of outpouring (the former being submarine and the latter subaerial), and in part by association with

¹ Termed "malchite" in the Ben Nevis and Glencoe Memoir.

earth-movements of different kinds. On the one hand, the calc-alkaline character of the rocks is a result of the close connection between the Caledonian movements and the uprise of the magma that formed the Old Red Sandstone igneous rocks. On the other, the Devonian area was far removed from the parts affected by the Caledonian revolution: it was an area of subsidence, and in the

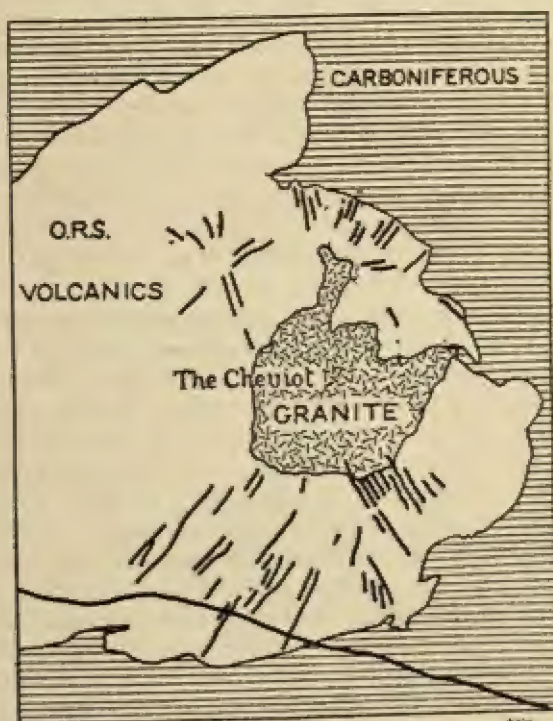


FIG. 142

Sketch-map to illustrate the Old Red Sandstone igneous cycle in the Cheviot Hills. Dykes are shown by thick lines. (After H. Kynaston.)

opinion of some petrologists this leads to the development of an albite-rich magma, giving rise to such rocks as albite-basalt (spilite) and albite-trachyte together with albite-dolerite.¹

The main igneous cycle ceased in Lower Old Red Sandstone times, but in one or two localities there were feeble revivals of activity in Middle and Upper Old Red Sandstone times. The andesitic lava of

¹ Dewey and Flett, *Geol. Mag.*, 1911, p. 246

Rhynie in Aberdeenshire is of the former age, while in the Orkneys lavas and pyroclasts occur both in the Middle and the Upper O.R.S.

In the region of the Orkneys, north of the Scottish mainland, an explosive eruption of great violence brought to a close the period of folding and erosion that immediately preceded Upper Old Red Sandstone times. The products of the explosion were spread as a thick ash-band over a wide area, and this is succeeded by a flow of olivine-basalt in the island of Hoy. Later still, the rocks, up to and including the Upper Old Red Sandstone, were cut by numerous dykes which "form a petrological group of remarkably interesting characters" that cannot be exactly matched anywhere else in Britain.¹ The dyke-rocks include leucocratic types, but the majority are melanocratic and thoroughly basic. The most interesting of the former are bostonites that are very typical examples of their kind: normally highly feldspathic, one of them contains the highest percentage (nearly 11 per cent) of potash of all British analysed rocks, and consists almost exclusively of orthoclase. The melanocratic group includes three chief types: camptonites, three out of every four dykes falling in this category; monchiquites, to the extent of nearly a quarter of the whole number; and a few intrusive olivine-basalts. The camptonites may be regarded as the central type. They contain small olivines, augite is universal and is a zoned variety, with green (perhaps chrome-diopside) cores, surrounded by mantles of titanaugite. A third mafic component is basaltic hornblende. With the incoming of porphyritic plagioclase and the elimination of the basaltic hornblende the camptonites grade into the basalts; while in the opposite direction, with the elimination of feldspar, they pass into monchiquites. In these the two essential constituents are olivine and augite, the latter making up two-thirds of the rock, embedded in brown glass, not in analcite, which, however, occurs in steam cavities and ocelli. Nepheline may occur as small crystals in the groundmass or as micropoikilitic patches. Finally, some varieties are rich in megascopic biotite and approach closely to alnöite. Comparison of the available analyses shows a fairly close correspondence between these monchiquites of the Orkneys and nepheline-basalts, suggesting that the former are the dyke-equivalents of the latter; but the monchiquites are rather poorer in silica, alumina and alkalis, thus stressing their melanocratic character and lamprophyric facies.

The age of these dykes is uncertain: they differ in type from the Old Red Sandstone dykes of other parts of Scotland, and may be either Carboniferous, Permian or Tertiary. In this connection it is significant that both camptonites and monchiquites are recorded

¹ Flett, Sir J. S., in "Geology of the Orkneys," *Mem. Geol. Surv. Scotland*, 1935. p. 173.

from among the Permian dyke-rocks of Ayrshire, while one of the Permian vent-agglomerates in the same area has yielded blocks of monchiquite containing xenocrysts of anorthoclase.¹ At least one of the Orkney monchiquites also contains these xenocrysts, a fact which, taking into account the extreme rarity of such rocks, affords strong evidence that both occurrences are of the same age, *i.e.*, Permian.

¹ Eyles, V. A., in "Geology of North Ayrshire," *Mem. Geol. Surv. Scotland*, 1930, p. 288.

CARBONIFEROUS TO TERTIARY IGNEOUS ACTIVITY

CARBONIFEROUS

During the Carboniferous Period Scotland was again the scene of widespread and long-continued igneous activity. In England contemporaneous eruptions led to the accumulation of volcanic ash and lavas in Derbyshire and the Isle of Man; while in Devon and Cornwall, as we have already seen, the period of activity which commenced in Middle Devonian times persisted into the early part of the succeeding period. In each of these localities the cycle was incomplete, being limited to the extrusive phase and the phase of minor intrusions. There are no plutonic rocks comparable in size with the Caledonian and Old Red Sandstone bosses of granite.

(1) SCOTLAND

It is significant that the unstable area of the **Midland Valley of Scotland** was the site of most of the volcanoes of Lower Carboniferous age. The earliest eruptions occurred in the east, in the neighbourhood of North Berwick, and, as is usually the case, the lowest volcanic rock is a typical explosion-tuff. This is succeeded by a considerable thickness of basalt-flows, which, as a result of subsequent movement, are inclined towards the west, in which direction the lavas become progressively more acid, indicating an increase in the acidity of the magma as time went on. Thus, in the Garleton Hills the basalts are succeeded by thick sheets of trachyte. Farther to the west, in Midlothian, lavas of the same age (Calcliferous Sandstone) occur as outliers, as at Arthur's Seat, in Edinburgh, where they rest on the Cementstone Group; and on the north bank of the Firth of Forth between Burntisland and Kirkcaldy. In the latter localities the eruptions were slightly later in date, belonging to the higher part of the Calcliferous Sandstone, and extending up to the base of the Carboniferous Limestone. Still farther west, extensive outcrops of Carboniferous igneous rocks occur which are mere relics of a widespread plateau of basalt. This is the Clyde Plateau of A. Geikie, and judging from existing outcrops, it must have once stretched continuously from Arran in the west to Stirling in the

east, and from the Highland Border southwards well into Ayrshire. A moderate estimate of the original area of the Clyde basalt-plateau is 2500 square miles. In the Glasgow district the lavas form the terraced slopes of the Campsie Fells in the north, the escarpments of the Kilpatrick Hills in the north-west, and the Cathkin Hills in the south. Petrographically these basalts are of the same types as those of the more easterly areas. Several volcanic necks, some of considerable size, have been located. It is probable that the stacks of North Berwick Law and the Bass Rock mark the sites of vents; while Arthur's Seat, in Edinburgh, is a composite vent, built partly of agglomerate and partly of vent-intrusions, which are lithologically identical with the associated flows¹ (Figs. 61 and 62). Such is the well-known Lion's Haunch (intrusive) basalt. Vents are also of common occurrence in the Clyde Plateau. Some are choked with basalt, while others are filled with agglomerate. The vent known as Meikle Bin in the Glasgow district is important, since the associated intrusions include (intrusive) phonolitic trachytes.

In the eastern part of the Midland Valley the volcanoes soon became extinct; but those occurring farther to the west persisted for a much longer period, and new vents were established, indicating a progressive migration of the centres of eruption to the west. Thus in the Bathgate Hills, in the neighbourhood of Linlithgow and Bo'ness, eruptions, which commenced late in Carboniferous Sandstone times, persisted into the Lower Limestone Group of the so-called Carboniferous Limestone of Scotland²; while at Bo'ness other flows are found in the Upper Limestone Group. This is also the case in the Saline Hills north of the Forth. Still later in date, in the Limestone Coal Group and Upper Limestone Group volcanic ashes are interstratified with the normal sediments at Dalry, North Ayrshire. Highly decomposed olivine-basalts chiefly of Dalmeny type (see p. 430) occur in the Millstone Grit of the West of Scotland. In Ayrshire³ these volcanic rocks reach a maximum thickness of some 500 feet at Troon; they extend northwards to Stranraer, westwards into Arran, and possibly across into Ireland in the Ballycastle coalfield. Their highly decomposed condition is due to contemporaneous weathering effected largely by acid water formed by rotting of the luxuriant vegetation which clothed the area at that time. The basalts in some cases have been converted into bauxitic clays.

A much more important recrudescence of activity took place in

¹ Flett, J. S., *Proc. Geol. Assoc.*, xxv (1914), pp. 14-18 and references.

² Falconer, J. D., *Trans. Roy. Soc. Edin.*, vol. xlv (1906), part i, p. 139.

³ Wilson, G. V. and MacGregor, A. G. in "Geology of North Ayrshire," *Mem. Geol. Surv.*, 1930, pp. 206 and 221.

Ayrshire in late Carboniferous to early Permian times. The lavas belonging to this subsidiary cycle occur in the Mauchline district, and are characterized by being more definitely alkaline in facies than the earlier rocks, since they include types with analcite and nepheline.¹

The only other important tract in Scotland where igneous rocks of Carboniferous age occur is near the Anglo-Scottish border, in the **Tweed Valley**. In this case, also, the present outcrop is a mere fragment of a basalt plateau, which has disappeared under the influence of erosion. To the west of the present outcrop there are numerous plugs of basalt and agglomerate which probably also belong to the Calciferous Sandstone cycle. This is the case with the interesting intrusions in the Eildon Hills, near Melrose, referred to below.

The Basic Lavas

The Carboniferous lavas of Scotland have been exhaustively studied by Hatch, Watts, and latterly by Tyrrell² and A. G. MacGregor,³ and detailed classifications have been evolved, based chiefly upon their mineralogical composition. The characteristic minerals of the Lower Carboniferous basalts are plagioclase, ranging in composition from oligoclase to bytownite, but labradorite is typical; a pale brown augite, occasionally with a tinge of mauve, though not with the full mauve tint of titanaugite; and olivine partly altered into serpentine or iddingsite. The accessories include orthoclase, analcite, biotite, hornblende, ilmenite and apatite. The three essential minerals are present in widely varying proportions: each may be absent from a particular specimen, while in another it may be the dominant constituent. In general there are two parallel series characterized by large (mega-) and small (micro-) phenocrysts respectively.

1. BASALTS WITH MEGAPHENOCRYSTS.

(a) *Dunsapie type* (Flett), with many large phenocrysts of plagioclase, augite and olivine, set in a fine-grained groundmass which may contain a little interstitial glass, analcite, chlorophaeite, etc.

2. BASALTS WITH MICROPHENOCRYSTS.

(a) *Dalmeny type*, with numerous microphenocrysts of olivine, fewer augites and sporadic labradorite.

¹ Tyrrell, G. W., *Geol. Mag.*, 1912, pp. 69-80 and 120-31.

² Tyrrell, G. W., *Trans. Geol. Soc. Glasgow.*, xiv (1912), pp. 219-57.

³ "Classification of the Scottish Carboniferous Olivine-Basalts, etc.," *Trans. Geol. Soc. Glasgow.*, xviii (1928), p. 324; and "Problems of Carboniferous-Permian volcanicity in Scotland" *Q. J. G. S.*, civ (1948), p. 133.

1. BASALTS WITH MEGAPHENOCRYSTS. (*contd.*)

(b) *Craiglockhart type* (Hatch), with large phenocrysts of olivine and augite, but none of plagioclase.

(c) *Markle type* (Hatch) really falls in a category of its own, as the only large phenocrysts are plagioclase (labradorite in the type-rock) associated with small olivines.

(d) *Kilsyth type* (Watts) is now regarded as a variety of Markle basalt with ophitic groundmass.

2. BASALTS WITH MICROPHENOCRYSTS. (*contd.*)

(b) *Hillhouse type* (Flett) with small olivines and usually fewer augites in a strongly augitic groundmass, sometimes partly glassy.

(c) *Mugeary type* (Harker) is an oligoclase-basalt with microphenocrysts of plagioclase. Olivine occurs in small crystals, and biotite and hornblende are accessories. Augite variable in amount.

(d) *Jedburgh type* (Watts) has small phenocrysts of labradorite and fewer small olivines, Augite restricted to groundmass.

It should be noted that these type-names are not restricted to lava-flows, but are applied also to small intrusive masses forming volcanic necks and sheets. Further, they represent arbitrarily chosen points in a continuously variable series.

Most of these types are widely distributed in the Midland Valley, but there appears generally to be a greater development of the more feldspathic types in the west than in the east. Thus, on the Little Cumbrae, the lavas are of the Markle and Mugeary types, while varieties richer in phenocrysts of coloured minerals are restricted to the numerous basaltic plugs and north-east or east-north-east dykes. In South Bute, however, the Markle, Mugeary, Jedburgh, Dunsapie and Craiglockhart types are all represented among the flows.¹

The Permian lavas of the Mauchline district of Ayrshire tend to be more basic, and, at the same time, more alkaline than the Lower Carboniferous basalts. They were emitted from sixty or more small vents which are lined with the materials forming the flows and choked with agglomerate. The lavas are largely olivine-basalts of the Hillhouse and Dalmeny types, but include also analcite-basalts, nepheline-basalts and limburgites. On the other hand the more felsic types, trachytes, trachyandesites, etc., are absent from the Permian lavas.²

¹ Tyrrell, G. W., "Igneous Geology of the Cumbrae Islands," *Trans. Geol. Soc. Glasgow*, xvi, part ii (1916-17), pp. 244-74.

² Tyrrell, G. W., *Trans. Geol. Soc. Glasgow*, xviii, part ii (1927-28), p. 259; also Eyles, V. A., MacGregor, A. G., "Igneous Geology of Central Ayrshire," *ibid.*, xviii, part iii (1930).

The Intermediate Lavas.

The less basic rocks, which are restricted to the main Lower Carboniferous cycle, are trachytes of various kinds. Some of them contain accessory nepheline, and may conveniently be termed phonolitic trachytes. The intrusions associated with these flows are of the same composition and texture as the latter, and in many cases it is impossible to state definitely whether the rock is a flow or an intrusion.

The phonolitic trachytes consist essentially of sanidine, with which is usually associated a little plagioclase, and a green and slightly pleochroic soda-augite, together with some nepheline. Such rocks form the laccolith of Traprain Law, the sill of Hairy Craig, and the stocks of North Berwick Law and the Bass Rock. The Traprain Law rock has recently been proved to contain a little sodalite in addition to analcite and nepheline, while the micro-syenite of the Bass Rock carries fayalite and nepheline.¹ In one case nepheline is sufficiently abundant to justify the use of the term phonolite. There is one exposure of this rock near Fintry, in the Campsie Fells.

A. G. MacGregor has recently described the Calciferous Sandstone lavas and associated intrusions from the fringe of the Clyde Plateau in North Ayrshire, and remarks that the occurrence of phonolitic trachytes here, as in the Garleton Hills farther east, emphasizes the alkaline affinities of the whole province. In this region also there is a unique nepheline-basanite in the same series, while the normal suite ranging from basalt to trachyte goes farther, yielding rhyolites.²

Trachytes are not uncommon in the central part of the Campsie Fells, round the Meikle Bin vent, where they form small elongated plugs or short dykes.³ Their state of preservation does not allow of detailed description, but it is claimed that there is here even a greater variety of types than is to be found among the trachytes of the Garleton Hills, East Lothian. Some contain "moss-like" pseudomorphs, which may well have been riebeckite originally. The latter mineral is found in the trachytes that occur as intrusions in the Eildon Hills. In some of the trachytes there is accessory quartz. In others large phenocrysts of sanidine are prominent, as at Peppercraig: these are perhaps best developed in certain rocks that are evidently links connecting the basalts with the true trachytes, *i.e.*, they are trachybasalts (of the Banak type), resembling closely the Yellowstone Park type-rock, in that plagioclase as basic as labra-

¹ Campbell, R., *Trans. Edin. Geol. Soc.*, xiii (1933), p. 126.

² "Geology of North Ayrshire," *Mem. Geol. Surv.*, 1930, p. 89.

³ Bailey, E. B., in "Geology of Glasgow District," 2nd Edn., *Mem. Geol. Surv.*, 1925, p. 185.

corite is associated with much sanidine. The latter occurs as a peripheral zone round the former in the groundmass, and locally as phenocrysts two inches in diameter, enclosing smaller plagioclase crystals.

The Intrusions.

As noted above, there are no plutonic intrusions belonging to this cycle, but the occurrence of ultrabasic plutonic rocks among the constituents of the agglomerates filling the vents and as numerous xenoliths in the basic lavas, points to the deep-seated presence of intrusions of such rocks as dunite, augite-peridotite, pyroxenite and biotite, none of which has as yet been exposed by denudation.

Minor intrusions are, however, numerous and varied in composition and habit. It has been pointed out that the main eruptions were followed by a revival of activity at three later periods: in the Carboniferous Limestone, in the Millstone Grit, and in the Permian. This makes it difficult to assign a definite age to any particular intrusion, and the precision that was possible in the case of the Old Red Sandstone cycle is here impossible. There is no clearly defined dyke-phase restricted to a relatively short interval of time; on the contrary the injection of the minor intrusions was spread over the whole of the cycle: the sills that are petrologically similar to the lavas with which they are interbedded were probably contemporaneous with these flows—the vent-intrusions and plugs certainly were. There can be little doubt that the trachytic plugs and other intrusions in the Midland Valley and in the Eildon Hills were contemporaneous with the upper lavas, of Cementstone age, in the Garleton Hills. Although the minor intrusions in the eastern part of the Midland Valley do not occur at higher horizons than the Carboniferous Limestone, in the western part of this tract they range as high as the red (?) Permian Sandstones in Ayrshire. In mineral composition these intrusions are clearly related to the Mauchline lavas, and were injected at a period somewhat later than the extrusion of the Permian lavas. They occur in the form of sills reaching 200 feet in thickness; and although they have a moderately wide range of composition, they are evidently co-magmatic and consist of different proportions of the following minerals: olivine, titanite, labradorite, ilmenite and analcite, with nepheline, barkevikite and other minerals as accessories. The occurrence of primary analcite in many of these intrusions has been satisfactorily established. Its presence in the magma undoubtedly decreased its viscosity, and hence allowed an unusual degree of differentiation, which is demonstrated by the stratiform nature of many of the larger intrusions. No intrusion in this cycle shows this more clearly than the Lugar Sill

in Ayrshire,¹ which includes some half-dozen distinct rock-types, e.g., analcite-gabbro, nepheline-gabbro (theralite), picrite, peridotite and lugarite.

Two series have been distinguished among these minor intrusions, one characterized by the presence of analcite and the other by the presence of nepheline. The former series includes analcite-syenite, a typical example occurring at Howford Bridge, Ayrshire, analcite-gabbros and analcite-dolerites (teschenite and crinanite). The most distinctive members of the second group are theralite and lugarite. There are intermediate types, containing both analcite and nepheline, such as the well-known essexites of Crawfordjohn and Lennoxton. Localized intrusions of basic lamprophyric rocks including camtonites and monchiquites occur in or near the Ayrshire vents.²

The most typical and the most widespread of these rock-types is teschenite, which is common in the Glasgow district, in Ayrshire, in East Lothian and Fifeshire. Augite-picrite is frequently associated with the teschenites, of which it is an ultrabasic differentiate. This is the case, for example, in the Inchcolm sill which forms an island in the Firth of Forth.³ Typical teschenite forms the Salisbury Craigs Sill on the outskirts of Edinburgh, and part of Gullane Hill on the Forth. The most distinctive of these rocks, so far as appearance in the hand-specimen is concerned, are the essexites, by reason of the large number of euhedral, porphyritic titanaugites they contain.⁴ An olivine-rich variety, which is correspondingly poor in feldspar and thus intermediate between the essexites and picrites, occurs at Benbeoch and elsewhere in Ayrshire, and has been termed "kylite."

The latest intrusions of the Carboniferous cycle are east-west dykes and some sills of quartz-dolerite and tholeiite, which cut, and are therefore later than, all the other intrusions. Petrographically they are unrelated to the earlier intrusions described above, and they bear no relation to the centres of Carboniferous volcanicity. They are, however, closely connected with the folding and faulting of late-Carboniferous times. They occur chiefly in the Midland Valley, and have been studied in the Kilsyth-Croy area, in the Bathgate Hills and in the neighbourhood of Stirling. Southwards they extend into northern England, and include the Hett dyke in Durham and the famous Whin Sill.⁵ In these rocks a pale brown monoclinic augite takes the place of the titanaugite of the teschenites

¹ Tyrrell, G. W., *Trans. Geol. Soc. Glasgow*, xxi (1948), p. 15.

² Tyrrell, G. W., *Trans. Geol. Soc. Glasgow*, xviii, part ii (1927-28), p. 281.

³ Campbell, R. and Stenhouse, A. G., *Trans. Geol. Soc. Edin.*, ix (1907), pp. 121-34.

⁴ Scott, A., *Geol. Mag.*, 1915, pp. 455-61, 513-19.

⁵ Holmes, A. and Harwood, H. F., "Age and Composition of the Whin Sill," *Min. Mag.*, 1928, pp. 493-542.

and associated rocks: it is often accompanied by orthorhombic pyroxene (not by olivine) and sometimes by pigeonite. The feldspar is a medium labradorite. The quartz occurs in patches of interstitial micropegmatite. A good example of quartz-dolerite is furnished by the sill at Ratho, eight miles east of Edinburgh, while an even more quartzose type occurs at Bowden Hill, Linlithgowshire. At their margins these intrusions pass into fine-grained basalts of much the same composition, termed tholeiites, and are of plateau-basalt magma-type.¹



FIG. 143

Sketch-map showing Carboniferous volcanic rocks (black) and quartz-dolerite dykes in Scotland and North England. The dykes occur in the two areas dotted in Scotland; only a few of the dykes are shown. (Based on maps by Dr. F. Walker and Prof. A. Holmes.)

(2) ENGLAND

The most extensive tracts of Carboniferous lavas in England are in **Devon and Cornwall**, where the rocks form a direct continuation of the Devonian cycle, so that no further description is necessary. Emphasis may, however, be laid upon the fact that there is very little in common between the lavas and intrusions of this and the Scottish region, except in a general sense: both series are essentially basic in composition; but in the case of the Scottish rocks primary differentiation had not removed the composition of the magma far from that of average basalt, although the tendency to migrate towards the "alkali pole" becomes noticeable towards the close of the

¹ Walker, F., "Palaeozoic Quartz-Dolerites . . ." *Min. Mag.*, xxiv (1935), p. 131.

cycle. On the other hand, the magma that gave rise to the spilites of the Devonian-Carboniferous cycle of South-West England was much more definitely alkaline at the commencement of the cycle, and this character persisted throughout the cycle, with little appreciable alteration in the composition of the magma.

In **Derbyshire** igneous rocks of Lower Carboniferous age occur in the *Dibunophyllum* zone in the neighbourhood of Matlock, Miller's Dale and Tissington. The lavas include basalts of two different kinds. Sheets of normal olivine-basalt occur in multiple flows with more alkaline types.¹ In the latter the dominant feldspar is oligoclase, together with some orthoclase, while augite is usually subordinate to olivine. These lavas are therefore oligoclase-basalts approximating in mineral composition to the Mugeary type of Harker. They occur, as do the "mugarites" of the Midland Valley of Scotland, in close association with normal olivine-labradorite-basalts, and may possibly be regarded as an alkaline scum drawn off from the top part of a basalt-filled magma-basin.

The lavas are associated with ashes and numerous sills of olivine-dolerite, and were presumably erupted from central volcanoes, since agglomerate-filled necks have been found in their vicinity. Locally the igneous rocks are termed "toadstone."

In the **Isle of Man** around Castletown the highest rocks referred to the Lower Carboniferous are porphyritic olivine-basalts, tuffs and agglomerates.

In northern **Somerset** a feeble development of basic lavas and associated intrusions is found in the neighbourhood of Weston-super-Mare. As in Derbyshire, the lavas occur high up in the Carboniferous Limestone, and are interbedded with normal marine sediments. They bear some resemblance to the spilites of Devon and Cornwall, but their state of preservation leaves much to be desired.

In the English Midlands basalts are associated with Carboniferous Limestone in the neighbourhood of Little Wenlock near the Wrekin, Shropshire, and with the Upper Carboniferous at Rowley Regis, Barrow Hill,² Pouk Hill, Kinlet, and the Clee Hills. Petrologically these rocks are closely similar, often extremely fine-grained analcite-bearing olivine-basalts, that is, analcite-basanites. Although some of these rocks are definitely intrusive, others are just as clearly extrusive.³ Thus the Titterstone Clee basalt is a sill; the Rowley Regis basalt is laccolithic; the Barrow Hill mass is intrusive. On the

¹ Sargent, H. C., *Q.J.G.S.*, lxxiii (1918), p. 21.

² Marshall, C. E., "The Barrow Hill Intrusion, S. Staffs.," *Q.J.G.S.*, ci (1946), p. 177.

³ Pocock, R. W., "The Age of the Midland Basalts," *Q.J.G.S.*, lxxxvii (1931), p. 1; but compare Marshall, C. E., "Field Relations of the Basic Igneous Rocks associated with the Carboniferous Strata," *Q.J.G.S.*, xcvi (1942), p. 1.

other hand the Little Wenlock basalt, which is finely exposed in quarries at Doseley, has been converted in its upper parts into a typical red bole, due to contemporaneous subaerial weathering. Although much of the Etruria Marl in the Upper Coal Measures in the northern Midlands superficially resembles red bole, the suggestion that it was formed of weathered basaltic material has not been generally accepted,¹ but in certain fine-grained breccias in the Etruria Marl (the so-called espley beds) abundant shards of volcanic material may well indicate the reality of eruptions at this time.

THE ARMORICAN INTRUSIONS

Just as the formation of the "Caledonides" was accompanied by the uprise of the "Newer Granites" and the intrusions associated with them, so the birth of the Armorican or Hercynian chains coincided with the emplacement of the granite masses of South-West England and the deeply denuded mountain belt stretching through "Armorica" into Spain. Five great laccoliths or bosses and several smaller satellitic intrusions occur in Devon and Cornwall: the former comprise the granites of Dartmoor (240 square miles), Bodmin Moor (or Brown Willy) (75 square miles),² St. Austell (33 square miles), Falmouth (or Carn Menellis) (50 square miles), and Land's End (75 square miles); while the Scilly Isles represent the highest points of a sixth large mass. The smaller intrusions include those of St. Michael's Mount, Godolphin, Carn Brea and Carn Marth, Belovely Beacon, Kit Down and Hingston Down. To what extent these apparently isolated outcrops are connected underground is unknown; but there is no doubt that the intervening stretches of killas are in some cases merely roof-pendants, and that further unroofing will extend the area of granite and diminish that of the country-rock. The granites occupy a belt of country having a Caledonoid trend; but they are individually associated with Armorican axes of uplift, and were injected into the crust near a line of weakness bordering the ocean.³ This weak tract not only determined the positions of the Armorican intrusions, but also the location of the Devonian-Carboniferous igneous rocks, and probably also of the Permian Exeter lavas (p. 442). The Armorican granites of this country are important not only from a petrological, but also from an economic point of view, because their intrusion was accompanied by a period of mineral emanation, when lodes were formed containing ores of tin,

¹ Robertson, T., "The Origin of the Etruria Marl," *Q.J.G.S.*, lxxxvii (1931).

p. 13.

² Ghosh, P. K., *Min. Mag.*, xxi (1927), p. 285.

³ Dewey, H. *Proc. Geol. Assoc.*, xxxvi (1925), p. 109.

the results of years of intensive study.¹ Their importance in the study of petrogenesis has been referred to above.

Such evidence as has been collected with reference to the form of the intrusions suggests a laccolithic rather than a batholithic habit: the fact that the granites appear to dip gently under the altered sediments into which they were intruded implies a domed roof; while in some cases, for example Dartmoor, a stratiform arrangement of the various intrusions that make up the mass suggests a sheet-like form. There is, however, little evidence as to the nature of the floor of the intrusions, and the petrographical similarity between the several granites is so pronounced that community of origin is undoubted, while the differences may well be due in part to varying depths to which they have been denuded.

It is evident that, like the Caledonian granites, those of Armorican age are composite intrusions. Recent work on the Dartmoor granite has shown that the mass consists of three chief members which were, as usual, intruded in the order of decreasing basicity.² The earliest intrusion was basic in composition, and is represented by numerous inclusions, some of large size, in the later intrusions. Next, the so-called "giant granite" was injected under a roof of killas, basic lavas, etc., and was later split into two or more sheets by a somewhat more acid "blue granite," which is a valuable building-stone. Minor intrusions in the form of narrow dykes, veins and thicker sills are common in both of the main intrusions. They are of granitic composition, but in some cases show wide variation from the main type.

The so-called "giant granite" is very coarse in texture, and rich in exceptionally large feldspar phenocrysts, which sometimes measure 7 by 5 inches and consist of coarse micropertthite. In the groundmass, micropertthitic orthoclase is associated with subhedral plagioclase ranging from albite to oligoclase. The dominant coloured mineral is biotite, with which is associated a subordinate amount of muscovite. Accessories are very variable, and in addition to those of normal occurrence in granites, such as zircon, magnetite and apatite, include others of pneumatolytic origin, namely, tourmaline, topaz, anatase and brookite, as well as minerals resulting from assimilation of country rock by the granite. Among these are abundant almandine garnet together with cordierite, andalusite, sillimanite, corundum and spinel. The "blue granite," which was intruded beneath the "giant granite," and was thereby protected from contamination by assimilation, is practically free from these highly aluminous accessories.

¹ See particularly "The Dartmoor Granite," *Q. J. G. S.*, lxxxviii (1932), p. 171 (with Harwood, H. F.).

² Brammall, A. and Harwood, H. F., *Min. Mag.* xx (1923), pp. 39-53.

The minor intrusions connected with the granites include basic as well as aplitic and pegmatitic "differentiates" of the main types. One of these, the Bittleford pegmatite on Dartmoor, contains a small amount of gold and silver of pyrogenetic origin. Of equally wide distribution are the many dykes of microgranite (some of them porphyritic), known to the miners as "elvans."

The dykes in Cornwall are stated to be arranged radially to the granite bosses, but locally there is a pronounced parallelism in their trend. Very few are found in the granites themselves: most occur in the synclinal tracts between the anticlines into which the granites were intruded; but there is reason to believe that the plutonic rock lies at no great distance beneath the surface in the areas where the dykes are concentrated.

The most widely distributed type of dyke-rock is a strongly porphyritic variety containing numerous feldspar phenocrysts up to one inch in length, together with bipyramidal quartzes and hexagonal biotites.¹ In the elvans associated with the St. Austell granite, porphyritic muscovite is not uncommon, while topaz, although widely distributed as an accessory, is especially characteristic of the intrusions near the Land's End mass. The dykes have suffered the same pneumatolytic modifications as the parent intrusions: they are often found to have been tourmalinized and kaolinized—in some cases tourmaline is the dominant coloured constituent.

The St. Austell granite is economically the most important of the Armorican granites. Having suffered more severely from the effects of pneumatolysis than any of the others, its deposits of china-clay rock and china-stone are more extensive, although they are not absent from the other masses; while veins of greisen and schorl-rock are common. The active agents which effected the alteration of the granite rose along vertical or highly inclined joints in the granite.

The metalliferous lodes occupy a broad belt of country embracing the northern half of the Land's End mass, the Redruth-Truro district north of the Carn Menellis mass, the St. Austell granite, the southern part of the Bodmin Moor intrusion, and terminates against the Dartmoor granite in the neighbourhood of Tavistock. Within this belt the dominant direction of the lodes is north-east to south-west, but south of Bodmin Moor it is north-south, and in the extreme east of the belt nearly east-west. The most important tin-mining area at the present time is that lying on the north-west side of the Carn Brea granite. From the petrological point of view, some of the most interesting of the metalliferous deposits are the wolfram-pegmatites, which are of very coarse grain, and are typically developed near Buttern Hill to the north of the Bodmin Moor

¹ "Land's End District," *Mem. Geol. Surv.*, 1907, pp. 61-67.

granite. Here microcline crystals up to three inches in length are intergrown with wolfram and quartz, while other constituents are apatite and tourmaline. These pegmatites often pass into veins of wolfram and quartz, and finally into pure quartz-rock. A detailed consideration of the genesis of the ores is outside the scope of this book, but it is interesting to note that a zonary distribution of the several ores, dependent on the temperatures of their formation, has been demonstrated.¹

The relation of the Armorican granites to the Exeter lavas is an interesting question, and it is probably identical with that connecting the Caledonian intrusions of Scotland with the Lower Old Red Sandstone lavas. Both series of lavas were extruded under sub-aerial, desert conditions; both rest upon an eroded land-surface from which they are locally separated by a small thickness of coarse arenaceous deposits; both were preceded by a period of plutonic injection.

In the Channel Islands granites are magnificently exposed in cliff sections, particularly in Jersey and Sark. In Jersey² the plutonic rocks include a wide range of types, red-weathering alkali-granite forming the north-western, south-western and south-eastern bastions. The north-western granite has stoped its way into earlier gabbroic sill-like intrusions, and is consequently crowded with xenoliths in all stages of dissolution. Because of assimilation of some of this basic material the red granite, which is normally deficient in coloured minerals and of leucogranitic type, is converted into a grey porphyritic rock, with clots and schlieren of hornblende and biotite. The basic xenoliths are now of dioritic (often tonalitic) composition—consisting essentially of hornblende and plagioclase, with quartz, orthoclase and biotite. Normally the original structure has been destroyed; but rarely small patches are seen to have survived, and these consist of labradorite and titanite in ophitic relationship. Therefore some of these Jersey diorites are amphibolitized (olivine-) gabbros. But in addition, dioritic rocks are widely developed in the north and south-east of the island, and include the same types of xenoliths as the granites. These are *magmatic diorites*, though they may well have been produced from the same materials as the *metasomatic diorites*, though more extensively, at some deeper-seated source. They include types with brown and green hornblendes varying in size between needle-like crystals to stout prisms several inches in length, showing a preferred orientation and particularly striking in certain pegmatitic facies. The proportion of black horn-

¹ See Dewey, H., *Proc. Geol. Assoc.*, xxxvi (1925), pp. 107-35, and references to the previous work of Maclaren, Cronshaw and Davidson.

² Wells, A. K. and Wooldridge, S. W., *Proc. Geol. Assoc.*, xlii (1931), p. 178.

blende to white feldspar varies and some varieties closely resemble the appinitic suite of the Scottish Highlands. Arrested stoping with widespread hybridization, the development of local pegmatitic clots and aplitic veins are well displayed at Elizabeth Castle, St. Helier, and much more extensively in the extraordinary maze of reefs laid bare at low tide off the south-eastern corner of Jersey.

The plutonic rocks are cut by sills, rarely of dolerite, more commonly of acid types—granophyre and microgranite, and large numbers of dykes of basalt, dolerite and mica lamprophyre.

PERMIAN

Igneous rocks of Permian age are found in only two areas in Britain—in Devonshire and in Ayrshire. The latter area has already been dealt with earlier in this chapter. The lavas of the Mauchline area are associated with red sandstones usually considered to be Permian.

In **Devonshire** the Permian lavas are restricted to the neighbourhood of Exeter, and are often referred to as the "Exeter traps." They were shown by Sir Henry de la Beche to lie at, or near, the base of the "New Red Sandstone," either directly on the Culm, or separated from it by a thin stratum of red rocks. The lavas were laid down upon a very irregular surface, from which rose prominent hills of Carboniferous (Culm) rocks. The main outcrops occur in the tongues of New Red Sandstone that extend westwards from the neighbourhood of Killerton and Tiverton. In addition, small patches of lava associated with Permian conglomerates rest on Devonian slates to the south of Dartmoor near Kingsbridge, and also south-west of Plymouth. The actual centres of eruption have been located in some cases. In others the lavas are regarded as of puy type. It is possible that other vents are hidden beneath the Permian rocks, but some evidence has been adduced which indicates derivation from the high land in the neighbourhood of Dartmoor. It is possible that the Dartmoor granite itself occupies the site of a magma-basin, capped with a roof of Culm sediments, from the upper surface of which rose several volcanic cones. In the unroofing of the granite mass the cones have of course been destroyed, but it is significant that blocks of acid and intermediate lavas occur in the Permian breccias, and decrease in size away from Dartmoor.

The systematic examination and determination of the rocks is rendered difficult by their extremely altered condition, the alteration dating from the Permian period. The lavas were the product of sub-aerial eruptions, and were extruded under desert conditions. Hence they suffered rapid disintegration, and their iron-bearing

constituents were quickly oxidized, which gives the rocks a characteristic red colour. The upper portions of the lavas are often much fractured (block lavas), and the crevices filled with sand. Many of the flows are extremely vesicular, and in their general appearance are strongly reminiscent of the Old Red Sandstone lavas of the Pentland Hills, etc., and the Permian lavas of Ayrshire.



FIG. 145.

Sketch-map showing distribution of the Exeter lavas and Devonian-Carboniferous volcanic rocks in Devonshire. (After W. G. Tidmarsh.) Permian Trias, spots; areas containing Permian lavas, ruled; Devonian and Carboniferous volcanic rocks, solid black.

The Exeter lavas have been investigated by Tidmarsh,¹ who divides them into ten types grouped into three series. Each of the types exhibits several different facies. Among the lavas and associated intrusions are some to which the names of normal rock-types

¹ Tidmarsh, W. G., "The Permian Lavas of Devon," *Q. J. G. S.*, lxxxviii (1932), p. 712.

may be applied, such as minette, rhyolite, quartz-porphyry. Most of the rocks, however, are of quite exceptional mineral and chemical composition. Among the features of special interest are: the occurrence of xenocryst-quartz-basalts; the lamprophyric facies of the lavas; and the occurrence at Loxbeare near Tiverton of a leucite-iddingsite-minette. The leucites are small but typical, and show the regular groupings of minute inclusions so characteristic of the small leucites in leucitites, etc. Apparently rapid chilling of the magma at a time when mica was in the process of formation gave rise to olivine plus leucite instead of more mica.

The problem of the origin of these rocks is the problem of the genesis of the lamprophyres. Tidmarsh's suggested solution involves interaction between the "depth residuum" of the Dartmoor granite on the one hand, and a late acid residuum on the other. Both consisted partly of crystals and partly of magma, therefore both sets of crystals would be unstable in the mixed liquid and would suffer corrosion in the manner described.

Although the range of composition of the Exeter lavas is small, it is significant that the Permian breccias contain abundant pebbles of strongly porphyritic microgranite rich in large phenocrysts of quartz and feldspar, also rhyolites and spherulitic acid lavas and andesites.

These Permian igneous rocks of South-West England form a small portion of a large petrographic province extending into Germany. On the Continent, however, the amount of igneous material is much larger and more varied in composition.

TERTIARY

Throughout the whole of the Mesozoic era there were no volcanic outbursts in the British area, but at the opening of the Tertiary era activity was renewed over an enormous area known as the **Brito-Icelandic** or **Thulean Province**, as it embraces North-West Britain, and extends thence northwards into Iceland, Spitzbergen, the Faeroe Islands and Jan Mayen. In Britain the volcanic forces quickly exhausted themselves; but in Iceland they have persisted until the present day. The Tertiary igneous rocks have not been subjected to any important earth-movements since their formation, and they are magnificently exposed in the hilly country of the Hebrides, in Ulster, and in hundreds of miles of coast sections. The rocks are usually in a perfect state of preservation, and are thus eminently suitable for detailed petrological research. It is only to be expected, therefore, that our knowledge of the Tertiary cycle is more detailed and complete than is the case with any other. Although

the cycle was completed in Britain in such comparatively recent times, profound pre-Glacial denudation has laid bare the plutonic rocks in some places, although in adjacent areas several thousand feet of lavas have escaped erosion.

The cycle consists of the usual three phases. In the volcanic phase and that of the minor intrusions it has proved possible to distinguish events that affected the whole or nearly the whole of the province, from those that were restricted in distribution to the neighbourhood of certain centres. Thus, in addition to the "regional" eruptions of basalt over the whole area there were "local" centres of eruption whose products were in some cases markedly different from the regional types. The centres of eruption that have been recognized in the British area comprise St. Kilda, fifty miles west of the Hebrides, Central Skye, Southern Rum and South-East Mull, all in the Hebrides, North and Central Arran in the Firth of Clyde, and Ardnamurchan on the mainland, the Mourne Mountains and Slieve Gullion in North-East Ireland. The time sequence of the several events in the cycle has been most clearly demonstrated by Harker¹ in Skye, and the succession there established is no doubt applicable to other parts of the province; but the recent work of Bailey and his collaborators in Mull has shown that this is not everywhere the case, and that there may be considerable divergence from the Skye sequence in the neighbourhood of individual centres. Opinion has changed as to the manner of eruption of the lavas. Geikie believed them to have been erupted from large numbers of fissures having a general N.N.W.-S.S.E., or N.W.-S.E. alignment; but Richey regards them as the products of great volcanoes of the "central" type.² The basalts were poured out with a minimum of explosive action, so that no pyroclasts worthy of mention occur between the flows. The lavas were extruded under sub-aerial conditions, and frequently the interval between one flow and the next was sufficiently long for the former to be deeply weathered into a red clay or "bole," prior to burial beneath subsequent flows. The few interbedded sediments which do occur include fluvial and lacustrine deposits, together with thin coals. The Ardtun plant beds are important since they have yielded valuable information as to the date of the eruptions. The remains of trees completely engulfed in basalt have been discovered in Mull, proving that one at least of the basalts overwhelmed an Eocene forest. The central parts of the flows are so massive as to be indistinguishable from the associated minor intrusions, but the higher parts are very vesicular, sometimes

¹ "Tertiary Igneous Rocks of Skye," *Mem. Geol. Surv.*, 1904.

² Richey, J. E., "The Tertiary Volcanic Districts" (British Regional Geology), 2nd Edn., 1948.

brecciated, and frequently very slaggy. This allows rapid denudation of the tops of the flows, and gives rise to a distinctive terraced type of scenery. Many of the lavas are beautifully columnar: the Giant's Causeway, and the lava exposed in the walls of the caves at Staffa, are typical examples.

The basalts in Tertiary times must have formed a vast plateau which has been largely destroyed by denudation. They still cover an area of 2000 square miles in Britain, however, and locally considerable thicknesses have survived: for example, 6000 feet in Mull, 2000 feet in Skye, but only 300 feet in the Ardnamurchan Peninsula.

In their petrographic characters, the basalts are typical of their kind and of simple mineral composition. From the point of view of their distribution as well as their petrology they fall into two groups:

1. The Plateau Group.
2. The Central Group.

The former group commences with tholeiites, often beautifully columnar, as at Fingal's Cave and the Giant's Causeway,¹ followed by the main suite of olivine-poor basalts. Among the higher flows in this category are some mugearites and feldspar-phyric basalts.

The basalts of the Central Group are rich in olivine and are preserved chiefly in great explosion vents or caldera.

In addition to the widespread eruptions of basalt there were local paroxysmal outbursts from the central volcanoes, which gave rise to thick accumulations of agglomerate, locally reaching 1000 to 1500 feet in thickness. Some of these volcanoes persisted for a long time, and during their existence experienced many changes in form and in the character of the eruptions and the materials erupted. Thus the Mull volcano was one of unusual complexity and "with every conceivable type of eruption represented by its lavas, agglomerates and intrusions." For long periods it was an extensive lava-cone of Hawaiian type, comparable with Kilauea, and it was from such lava-cones that many of the basalt-flows of Mull were erupted. During periods of depression the cone became the site of a crater-lake, into which basalts of the Central Group were poured and formed typical pillow-lavas, consisting of variolitic basalts. A feature of some interest is the widespread alteration of the lavas in the neighbourhood of the central volcanoes: over an area some sixteen miles in diameter, the Mull basalts are characterized by a rich development of albite, epidote and chlorite, while the olivine is completely serpentinized. These alterations resulted from pneuma-

¹ Tomkeieff, S. I., "The Basalt Lavas of the Giant's Causeway District of Northern Ireland," *Bull. Volc., Naples, Série II, Tome VI, 1940, p. 89.*

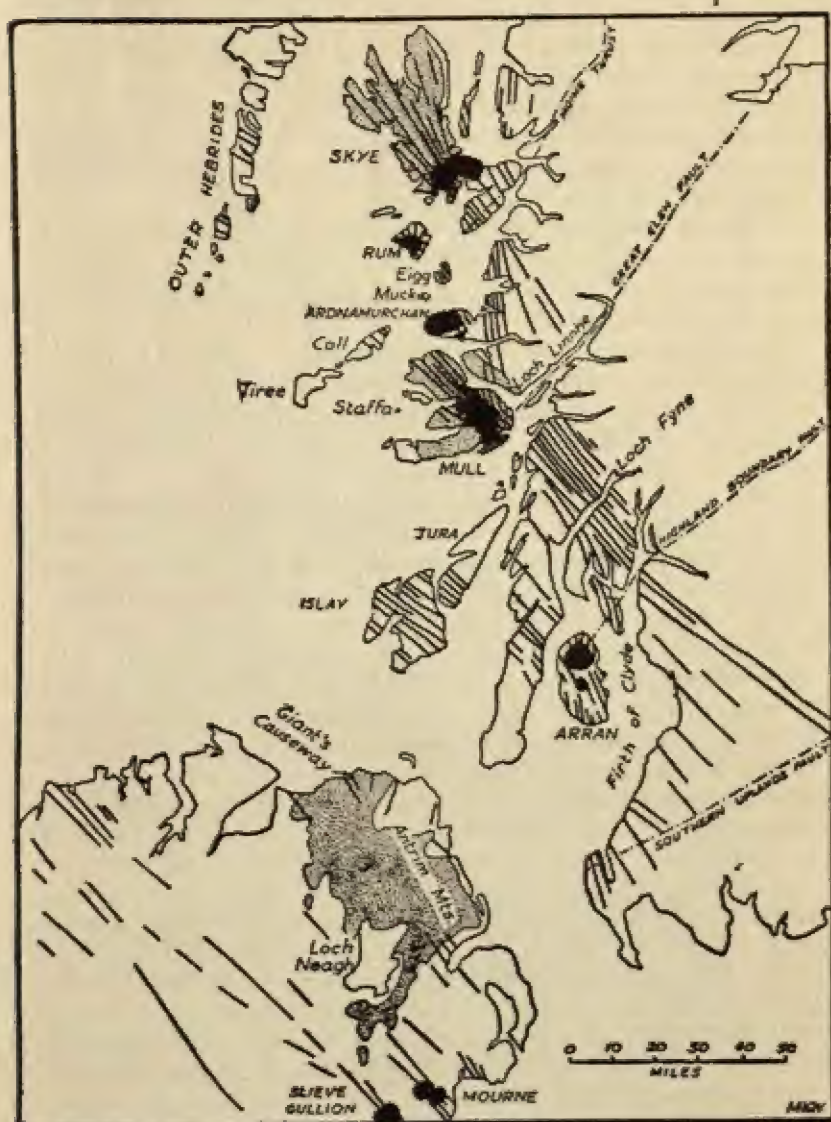


FIG. 146

Map of the Tertiary igneous rocks of Scotland and northern Ireland.
 (Based on maps by the officers of the Geological Survey.)

tolitic or solfataric action, and were consequently pene-contemporaneous with the eruptions themselves.

Lavas other than basalts are of very local distribution, but are found, for example, in Skye dovetailing into the basic flows. Trachytes and rhyolites both occur, the former underlying the latter. In Mull rocks of similar composition are found, not as flows, but as agglomerates and plugs, due no doubt to the high viscosity of the trachytic and rhyolitic magmas.

A complete series of rock types ranging in composition from ultrabasic to thoroughly acid is found among the plutonic intrusions, but two rocks are dominant over the others, namely, granite and gabbro, or their textural variants.

Harker has shown that in Skye the earliest plutonic intrusions were peridotites, but that these have been largely destroyed by the later more acid intrusions. Ultrabasic rocks are more abundant in Rum,¹ where they form an interesting complex in the neighbourhood of Mounts Allival and Askival. These hills consist of a large number of sheet-like injections of two contrasted rock types: one a true peridotite, composed of olivine, augite and anorthite, with chromite as a prominent accessory, and the other, anorthite-troctolite (allivalite of Harker), consisting of anorthite and olivine. Harker believed that the sheets, which vary from 100 to 150 feet in thickness, were intruded successively, the highest being the oldest, and the lowest the youngest of the series of intrusions². The process by which the two partial magmas were differentiated is illustrated by the partial separation of the component minerals of the individual sheets: in the peridotites there are layers consisting essentially of chromite; some contain olivine to the almost complete exclusion of other minerals; while in the allivalite sheets are streaks dominantly feldspathic.

Following the ultrabasic rocks came larger intrusions essentially laccolithic in form and basic in composition. In Rum these gabbros have invaded the base of the ultrabasic complex, while in Skye gabbro is the dominant rock type in the great intrusion which builds the Cuillin Hills (Fig. 147). The age relationship between the two intrusions is shown by the occurrence of a wide belt of intrusion-breccia between the two, within which there is a passage from peridotite penetrated by thin veins of gabbro, through a belt in which the two rock types are inextricably intermingled, to gabbro with occasional xenoliths of peridotite. The gabbros of Skye first attracted attention on account of their marked banding, due to the concen-

¹ "The Small Isles of Inverness," *Mem. Geol. Surv.*, 1905, pp. 68-92.

² Cf. Tomkeieff, S. I., "On the Petrology of the Ultrabasic and Basic Rocks of the Isle of Rum," *Min. Mag.* xxvii (1945), p. 127.

tration of the component minerals in streaks and lenticles drawn out by flow-movements in the rock when in a semi-molten condition. In these basic rocks the feldspar is usually labradorite; but sometimes anorthite takes its place, as in the eucrite type. Again, although the pyroxene is normally diallage, it is not infrequently accompanied by hypersthene, yielding hypersthene-gabbros or norites according to the proportions of the two kinds of pyroxene (p. 277). Both olivine-

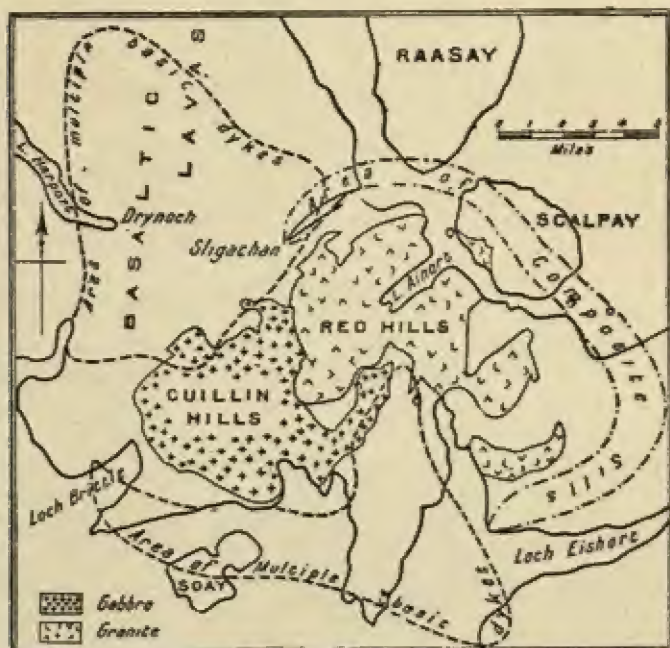


FIG. 147

Map of a portion of the Isle of Skye, showing the distribution of the gabbro and granite, and of the multiple basic dykes and composite sills.

(After A. Harker.)

bearing and olivine-free types of gabbro and eucrite occur. Basic rocks of these types make up the greater part of the Ardnamurchan peninsula, and are also important in Mull and Arran.

The basic rocks were succeeded by major intrusions of acid composition, which, in general, were injected beneath the earlier intrusions, though to some extent invading them and producing interesting hybrid types along the contact zones. The most important of the Tertiary granites occur at Goatfell in Arran (36 square miles), the Mourne Mountains (220 square miles) in North-East

Ireland, the Red Hills in Skye and at St. Kilda. The Mourne complex (Fig. 148) has been studied by Richey,¹ who has shown it to include four members differing somewhat in composition and texture. In the Tertiary granites there is a marked tendency towards the development of the micrographic texture. The greater part of the Red Hills granite is of this type, while "granophyre" (graphic microgranite) is typical of the acid intrusions of Mull and Rum (Orval). The close association of gabbro (or dolerite) with granite (or granophyre) is nowhere better illustrated than among the Tertiary igneous rocks. Intermediate plutonic types are conspicuously absent; where they do occur they may be suspected of being of hybrid origin. Although there is clear evidence in Skye that the granite was subsequent to the gabbro and invaded the latter from beneath, a totally different relationship exists between the acid and basic rocks in Mull and the other centres. Here the form of the intrusions is distinctive: the major intrusions have the form of rather irregular ring-bosses or ring-dykes (p. 153), that is, they occur as more or less vertical sheets of arcuate cross-section.² They range in thickness up to more than a mile and extend downward to considerable depths. In such bodies gravitational differentiation has every opportunity of bringing about marked contrasts in composition between the rocks of the upper and those of the lower parts of the intrusions. A typical example in Glen More, Mull, shows, in a vertical section of 1500 feet, a range in specific gravity from 3.06 to 2.50. There is a gradual transition from coarse gabbro at the base to graphic microgranite at the top, both rocks being quite typical, and being evidently differentiated from the same body of magma, the splitting having been effected in place. The gabbro may be regarded as consisting largely of sorted crystals of early formation, while the microgranite may represent the liquid residuum which was squeezed out during crystallization and injected into the upper parts of the arcuate fracture, being chilled against the cool country-rock.³

The detailed study of the ring complexes has shown the sequences of events about any one centre to have been extraordinarily complex. In Skye and Rum the sequence as interpreted by Harker was simple, and the magma changed in composition from ultrabasic to acid during the plutonic phase and back again to ultrabasic in the ensuing "hypabyssal phase." No such simplicity is found in Mull and Ardnamurchan, and there is no evidence of a systematic change

¹ "Structural Relations of the Mourne Granites," *Q.J.G.S.*, lxxxiii (1928), p. 658.

² Richey, J. E., "Tertiary Ring Structures in Britain," *Trans. Geol. Soc. Glasgow*, xix (1931-32), p. 42.

³ "Tertiary and Post-Tertiary Rocks of Mull," *Mem. Geol. Surv.*, 1925, p. 306.

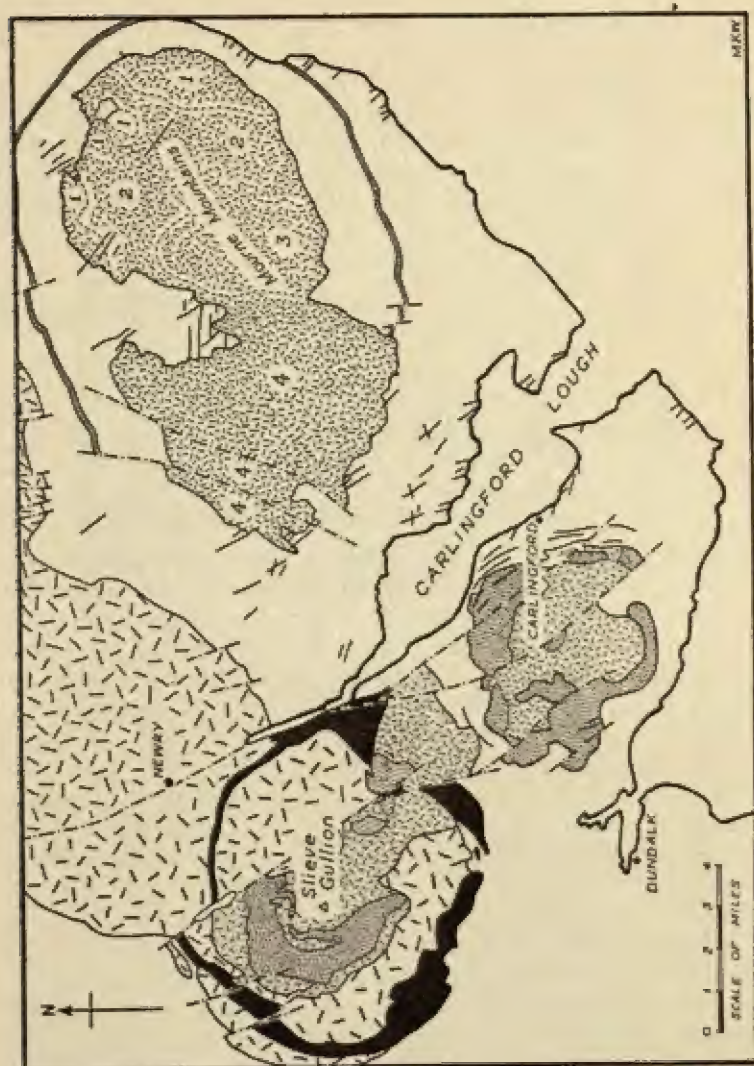


FIG. 148

Map of part of north-eastern Ireland showing the igneous complexes of the Mourne Mts., Carlingford and Slieve Gullion.

Newry granodiorite (Caledonian), large dashes; Mourne Mts. granite, small dashes; Tertiary gabbros, stippled; granophyres, dot-dash ornament; the acid ring-dyke of Slieve Gullion, black. One cone sheet is shown round the Mourne granites, which are numbered in order of intrusion. (After Rickey, Reynolds, Tomkeieff and Marshall.)

in the nature of the magma. On the contrary, there are almost bewildering alternations of different kinds of gabbros and eucrite with "granophyre."

The mapping of the complexes has shown that from time to time the centres of eruption and of intrusion changed their position. Thus there are two centres in Mull and three in Ardnamurchan. As shown in Fig. 149, in Ardnamurchan the rocks of the second centre truncate those of the first, while those about the third truncate

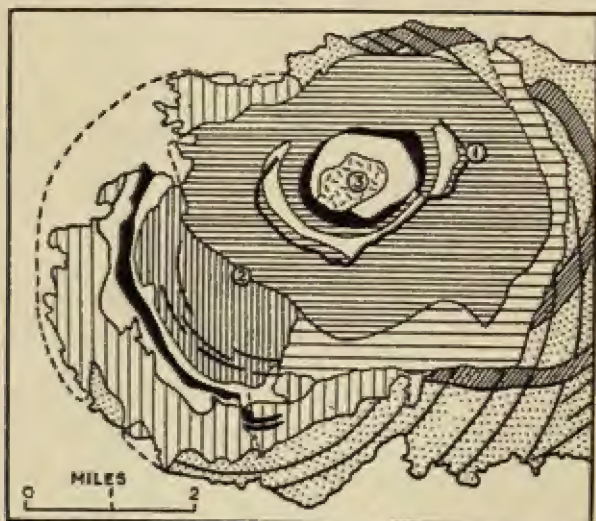


FIG. 149

Simplified sketch-map of central intrusion complex, Ardnamurchan, Scotland. Ring-dykes of centre 1, oblique ruling; of centre 2, vertical ruling, and black and white; of centre 3, horizontal ruling, and black and white. Tonalite of centre 3, small dashes. Sediments, lavas, etc., spots. A few cone-sheets round centres 1 and 2 are shown. (Based on maps in *Ardnamurchan Memoir*, 1930.)

those of the second. The third is perhaps the most instructive of the ring complexes as it is perfectly preserved and shows a good range of rock-types, including successive rings of gabbro, eucrite, tonalite and monzonite. As these rocks differ in their resistance to denudation, the structure has been beautifully etched out and gives a unique panorama of concentric hill-ranges with intervening valleys.

The Minor Intrusions

The Tertiary minor intrusions may conveniently be divided into two groups, (1) regional, and (2) local.

Intrusion on a regional scale took the form of swarms of basic dykes having the general north-west to south-east direction.

In connection with the local centres, the rocks of the minor intrusions were much more variable in form and in composition. Dyke-rocks are found closely allied in composition to each of the plutonic types noted above, that is, there were three chief groups corresponding with the acid, basic and ultrabasic major intrusions, and in Skye they were injected in the order named.

The earliest of the post-granite minor intrusions in Skye were composite sills consisting of an earlier basic member (basalt), followed by a later acid member (graphic microgranite) which usually split the former down the centre. They are restricted to an arcuate belt lying north-east of the granite of the Red Hills (Fig. 147).

The local minor intrusions of acid composition are clearly related to the great granite intrusions, but are slightly more acid than the latter rock. In texture they vary considerably. Some are typical porphyritic microgranites with large phenocrysts of quartz and feldspar set in a groundmass which varies from microcrystalline to cryptocrystalline. Some of the visible offshoots from the granites are indistinguishable from rhyolites. In a parallel series the quartz and feldspar of the groundmass are intergrown, yielding micrographic, cryptographic and beautifully spherulitic rocks. Rarely these rocks become less acid, and by failure of the quartz pass into microsyenites, which in Skye and Arran closely approach trachytes in general appearance. These are the "bostonites" and "orthophyres" of Harker.

In areas near to the granites, intrusions of a late date include tholeiites and pitchstones, often associated together in composite intrusions, though both do occur alone. The pitchstones in particular are interesting on account of their rarity. First recognized by Jameson about 1700, they were more fully described by Judd, but new features, such as the occurrence of fayalite, are still being brought to light by careful examination. The best known are the pitchstones of Arran and of Eigg. In the former island they occur as sills, but more commonly as composite dykes, such as those found on the foreshore at Tormore, associated with strongly porphyritic microgranites and tholeiites.

In Mull the latest of the local intrusions, cut only by the north-west dykes to be described below, is the unique ring-dyke which surrounds the north-west caldera. This intrusion, termed by the Geological Survey the Loch Bà Felsite, is usually about a hundred yards in width, though ranging up to a quarter of a mile. The maximum diameter of the ring is about five miles. A surprising fact is the fineness of grain of the rock itself. Much of it is a beautifully flow-

banded rhyolite, passing in places into a slightly more crystalline "felsite" (Fig. 150). In places the normal rock passes into a breccia consisting of fragments of acid rock of variable texture, including "granophyre" and flow-banded rhyolite, together with some basic rock, all invaded by tongues of spherulitic rhyolite. The acid magma

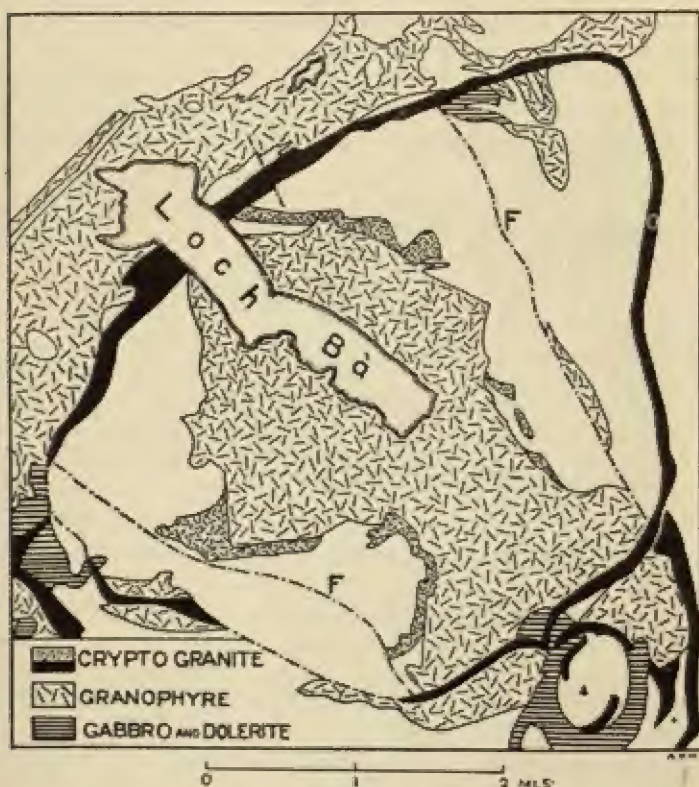


FIG. 150

A Tertiary ring-dyke and associated intrusions, Loch Bà, Mull. (After E. B. Bailey and others, in "Tertiary and Post-Tertiary Geology of Mull," *Mem. Geol. Surv.*, 1924.)

advancing up the ring-fissure would be very viscous, and on arriving near to the surface would doubtless suffer flow-brecciation, and possibly brecciation due to explosions at the top of the column. There can be little doubt that the intrusion worked its way to the surface, the higher part being cooled under atmospheric conditions and hence reproducing many of the textures of true extrusive rhyolites.

Local minor intrusions of basic composition are in like manner related to the great gabbro and eucrite intrusions: they occur in large numbers in the neighbourhood of the gabbro of the Cuillin Hills in Skye, round the eucrites of Ardnamurchan, and in Mull, Rum and Arran. Among them are the thick sills of crinanite in South-East Arran, and sills of crinanite and olivine-dolerite in northern Skye. Included in this category also are certain radially disposed dykes of basalt and dolerite, others that are tangential to the boundaries of the major intrusions, and the remarkable inclined sheets of conical form—the cone-sheets of Bailey. These were described by Harker from the Cuillin Hills, where they occur as segments of cones inclined inwards towards the centre of the gabbro laccolith at angles up to 45° . It has since been discovered that cone-sheets are developed on an even more spectacular scale in Mull and Ardnamurchan. In the former locality they are concentrically disposed around two centres of eruption. Their injection was not restricted to one short episode as in Skye, neither are they all of basic composition: some are acid, and the intrusion of cone-sheets, which started quite early, persisted in Mull intermittently until the close of the cycle. The early cone-sheets are innumerable. They are chiefly olivine-dolerites from 30 to 40 feet in thickness, and are somewhat irregular in their attitude as they repeatedly cut one another. The majority are inclined inwards at angles of about 45° . Somewhat later in date came another series of less basic, finer-grained cone-sheets, the rocks of which include variolites, tachylytes, basalts of the tholeiite type, and quartz-dolerites. These later sheets are so numerous that in a measured section the ratio of igneous rock to "screens" of country-rock is approximately 2 : 1.

Passing now to the consideration of the regional dykes we meet one of the most striking features of the Tertiary cycle: the dykes are remarkable not only on account of their vast numbers, but also by reason of their regularity of trend over a very extensive area. The regional direction differs little from north-west to south-east, indicating a tension acting at right angles thereto. The parallelism between this direction and the trend of Tertiary faults in other parts of Britain, and the fact that both are parallel to the extensive "deep" stretching north-westwards from the Bay of Biscay into the Atlantic, has been emphasized, and the fracturing has been explained as the result of crustal creep towards this "deep."¹ The localization of swarms of north-west dykes was no doubt due to the presence of wedges of basic magma lying at no great distance beneath the crust and causing belts of weakness. There is a marked tendency for the

¹ Evans, J. W., Presidential Address, *Q.J.G.S.*, lxxxix, 1925, especially pp. ci-ciii.

dykes in the neighbourhood of the plutonic centres to swing away from the regional direction and to crowd in towards the centres, while few occur in the intervening belts: the fractures occupied by the dykes crowd in towards the weak spots in the crust, rather than maintain their direction through adjacent stronger parts.¹ Thus the dykes are concentrated into "swarms": these comprise the Skye,

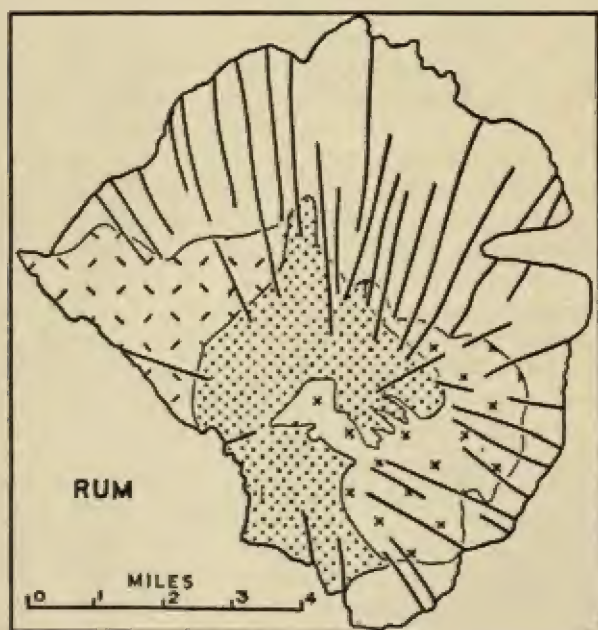


FIG. 151.

Sketch-map showing relation between radial dyke-swarm and plutonic intrusions in Rum. Ultrabasic, spotted; basic, crosses; granite, dashes; Torridonian, blank.

Rum, Mull, Islay, Arran, Mourne and Carlingford-Slieve Gullion swarms.

Although chiefly concentrated in the Hebrides, in the adjacent parts of the mainland of Scotland and in northern Ireland, Tertiary dykes are also found in northern England, for example, the Cleveland dyke; occasionally in the Midlands, such as the nepheline-olivine-dolerite of Butterton in North Staffordshire, while in North Wales they have been recorded from Anglesey² and various localities

¹ Evans, J. W., *op. supra cit.*

² Greenly, E., "Geology of Anglesey," *Mem. Geol. Surv.*, 1919, pp. 684-90.

in Carnarvonshire.¹ Those of North England have been shown to converge upon the Mull swarm,² while the Welsh dykes clearly belong to the Antrim swarm.

The dykes were formed from basic magma which, rising rapidly, suffered little contamination or differentiation. Essentially the dyke-rocks are dolerites or basalts according to their grain-size. Those of the thinner dykes are indistinguishable, under the microscope, from basaltic flows, and in a representative series from this suite, all stages from basalt-glass (tachylyte) to quite coarse ophitic dolerite may be found. In addition to normal olivine-bearing and olivine-free types, others bear evidence of a tendency on the part of the magma to migrate towards the alkali pole: common augite is replaced by deep purple-brown titanaugite, while there is a moderate amount of analcite, or other zeolite, in the interstices between the labradorite and other earlier formed minerals. These analcite-dolerites constitute the Crinan type of Flett, and it should be noted that no means of distinguishing between the "crinanites" in the north-west dykes (presumably of Tertiary age) and identical rocks found in close association with the Permian intrusions of the Midland Valley of Scotland has yet been discovered. Among the intrusive basalts, two types may be specially mentioned. One, first described from the Cumbrae Islands between Arran and the mainland, is a porphyritic basalt with large pale-coloured phenocrysts of anorthite set in a groundmass of laths of labradorite, enstatite and augite, with an abundant glassy base.³ The second type is an andesitic basalt with intersertal texture (tholeiite), the type-occurrence being the tholeiite of the Brunton dyke in Northumberland. These are of essentially the same composition as the rather coarser quartz-dolerites. In contrast to the other dyke swarms, that of Mourne consists largely of intermediate (andesitic) rocks.⁴

Among the latest minor intrusions are some of ultrabasic composition, which occur chiefly in radiating dykes in or near to the basic plutonic complexes. Petrographically they resemble the peridotites which were intruded at the commencement of the plutonic phase, and include picrites (with anorthite), augite-peridotites and dunites.

We have finally to notice a few scattered intrusions of rare rock-

¹ Matley, C. A., *Q. J. G. S.*, lxxix (1913), p. 525.

² Holmes, A. and Harwood, H. F., "The Tholeiite Dykes of the North of England," *Min. Mag.*, xxii (1929), p. 1.

³ Tyrrell, G. W., *Geol. Mag.*, 1917, pp. 305-15, 350-6.

⁴ Tomkeieff, S. I. and Marshall, C. E., "The Mourne Dyke Swarm," *Q. J. G. S.*, xci (1935), p. 251. See also Tomkeieff, S. I. and Marshall, C. E., "The Killough-Ardglass Dyke Swarm," *Q. J. G. S.*, xcvi (1940), p. 321.

types occurring on the outskirts of the Tertiary Province. These are of more strongly sodic character than the majority of the normal rocks of Tertiary age in this country, and include the nosean-phonolite that forms the Wolf Rock off the Cornish coast, the sodic granites of the island of Rockall, the riebeckite-microgranite of Ailsa Craig, and the riebeckite-trachyte of Holy Isle near Arran.

In the northern part of the mainland of the Shetland Isles an interesting suite of dykes occurs, trending north to south, and including riebeckite-microgranites, some porphyritic, others aphyric, and some beautiful spherulitic types. Their age is uncertain: they may be Tertiary, but are conceivably Carboniferous.¹

It remains to mention two other complexes which may be appropriately considered here.

Lundy Island² lies off the Somerset coast, well within range of the Armorican granites of south-western England. The island consists almost entirely of granite, cut by a varied assemblage of dykes. Petrologically the granite is much like the West of England types, the earlier intrusions being sodi-potassic, with perthitic orthoclase the dominant feldspar; but there is a larger proportion of albite-oligoclase in the later types. In certain points of detail the granites recall the Tertiary intrusives of the Mourne Mountains, particularly in textural similarities: the occurrence of miarolitic texture, with beryl and topaz in the cavities, among the normal minerals. Of the dykes over nine-tenths are basalts and dolerites—some are olivine-bearing, some quartz-bearing, some are classed as "tholeiites," while another link with the Tertiary Province is afforded by the pitchstones and occasional tachylytes like those of the Hebrides. Less acid dykes occur, some being trachytic and others termed "orthophyres" are microsyenitic.

Secondly, on maps showing the Tertiary dykes, a swarm unrelated to any of the visible volcanic centres crosses Islay and Jura. The inference is that a concealed complex lies a little distance from the coast of Jura.

With the close of the Eocene cycle, igneous activity ceased in Britain. Looking back over this brief account, one is struck by the variety of the rock types occurring among the British rocks, by the comparative perfection of the record so far as some of the cycles are concerned, and, on the other hand, by the many problems connected with the genesis, age and relationship of these rocks which still await solution.

¹ Dollar, A. T. J., "The Lundy Complex: its Petrology and Tectonics," *Quar. Journ. Geol. Soc.*, xcvi (1941), p. 39.

² Phemister, J., and others, "Riebeckite-bearing Dykes of Shetland," *Min. Mag.*, xxix (1950), p. 359.

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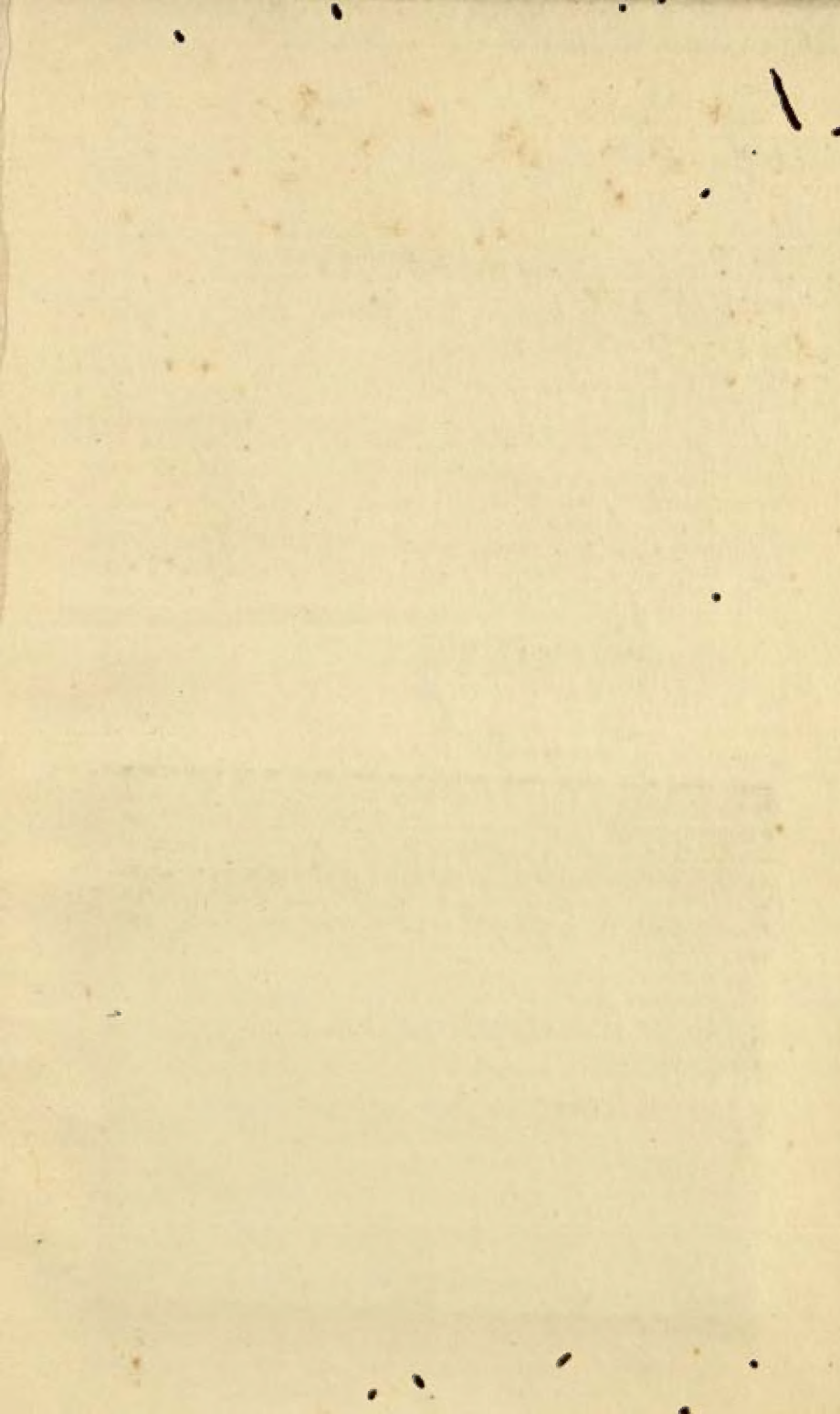
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